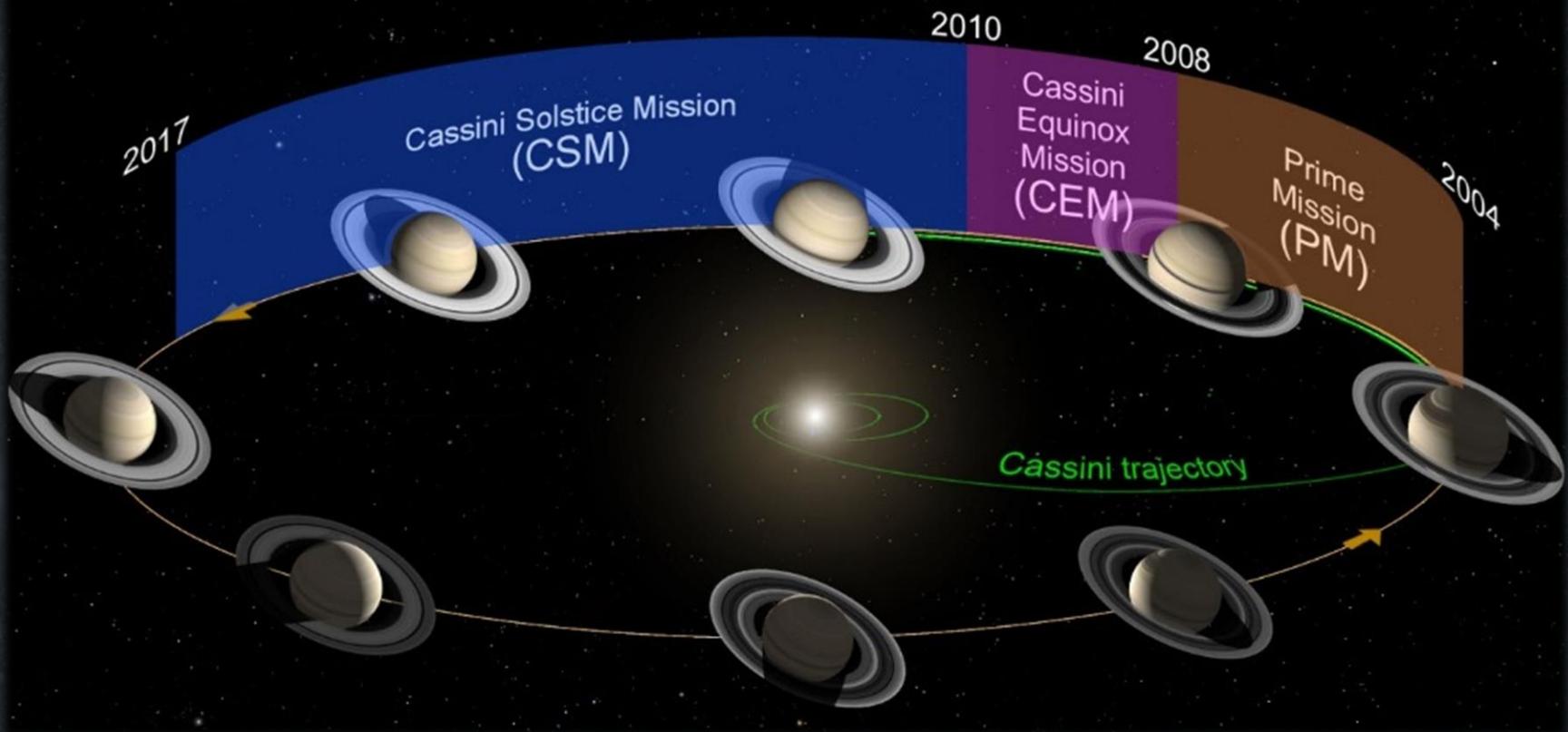


Diving Deeper: Exploring the Feasibility of Lowering Cassini's Final Orbits

Erick Sturm
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109

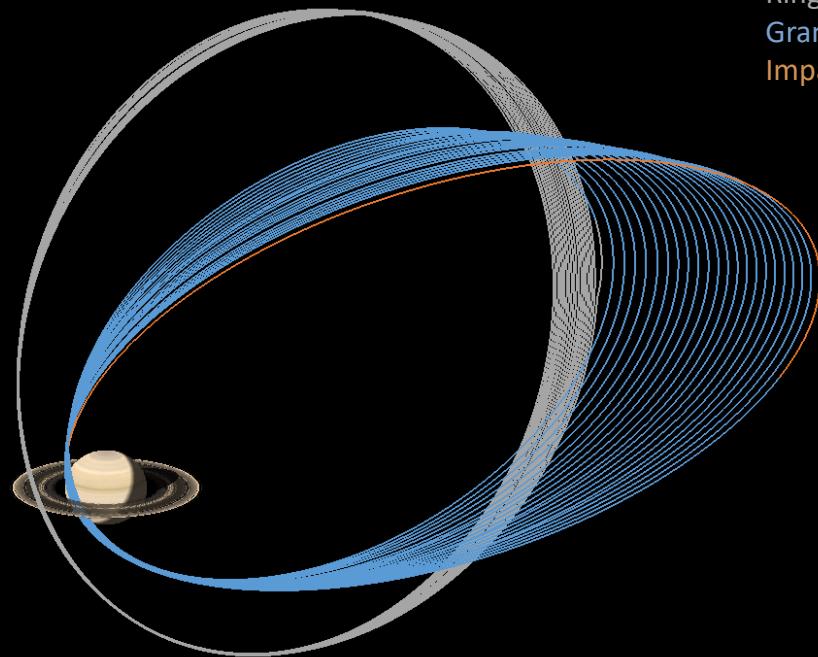
A Brief History of Cassini



Solstice Mission Trajectory



Ring-Grazing orbits
Grand Finale orbits
Impact orbit



Grand Finale Objectives

*Bringing Cassini closer to Saturn
than ever before*

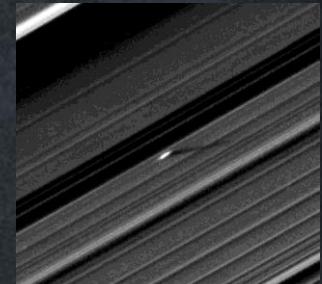
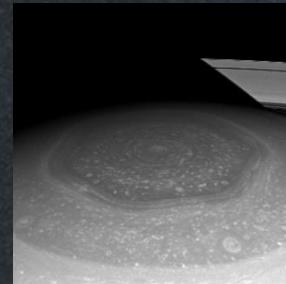
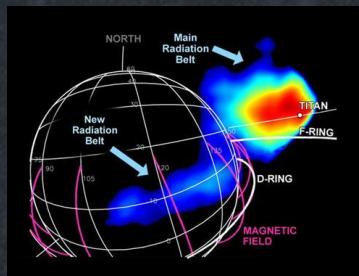
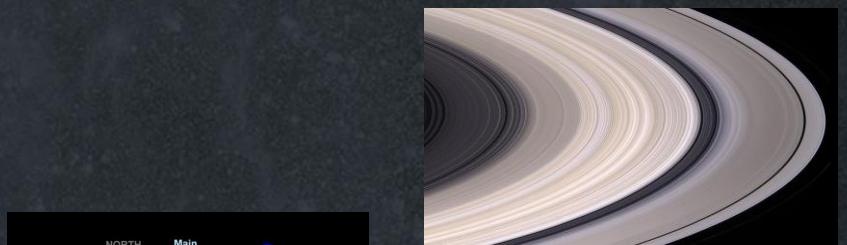
Planetary Protection

- Spacecraft disposal



Unique Science

- Saturn internal structure
 - Magnetic & gravity high-order moment measurements
- Ring mass
 - Address age of main rings
- In-situ measurements
 - Ionosphere, inner radiation belts, auroral region, and D ring particles
- High resolution observations
 - Rings, poles/aurora, atmosphere



Grand Finale Timeline



November 30, 2016

- F-ring Orbits Begin
 - 20 orbits
 - 3 maneuvers

April 22, 2017

- Last Targeted Titan Flyby
 - Produces Grand Finale trajectory

April 23, 2017

- Grand Finale Begins
 - 22½ orbits
 - 9 non-targeted Titan flybys



September 11, 2017

- Last Non-targeted Titan Flyby
 - Puts Cassini on impact trajectory

September 15, 2017

- Saturn Impact





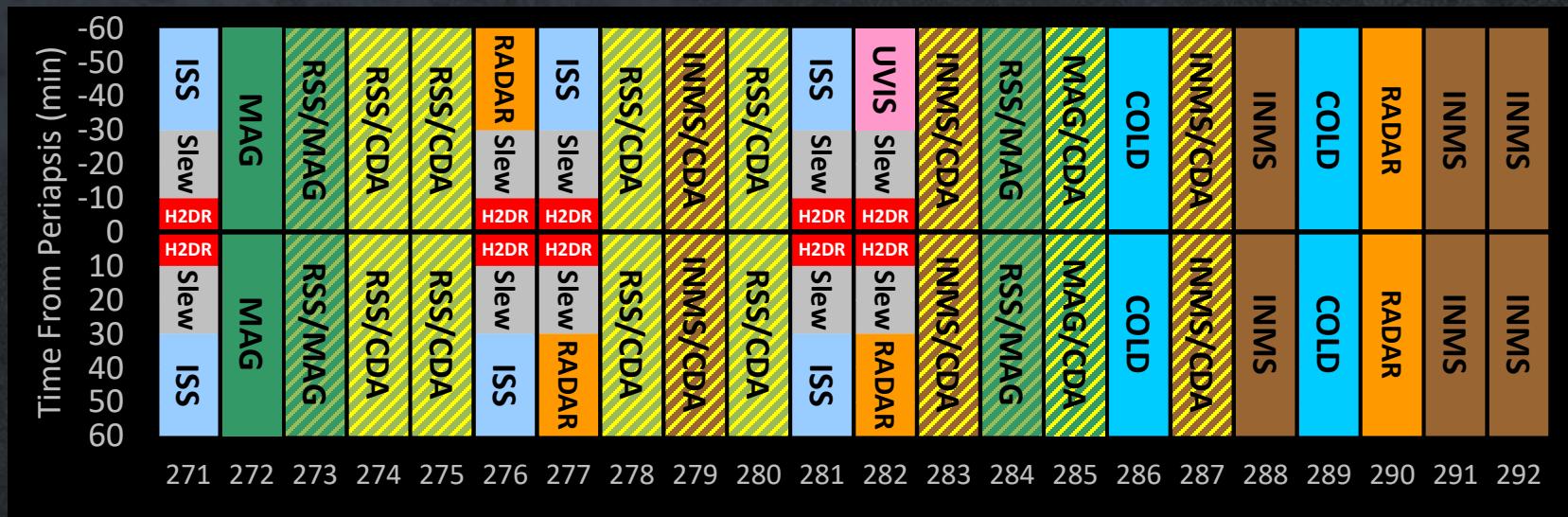
Proximal Pop-Down Scenario

Objective:

Determine the feasibility of lowering one of the final five periapses

Ground Rules

- Maintain a ballistic, Saturn-impacting trajectory
 - Maintain line-of-sight during “final plunge” & capture
 - Respect spacecraft health & safety limits
 - No impacts to “upstream” trajectory
 - Minimize impacts to “downstream” trajectory



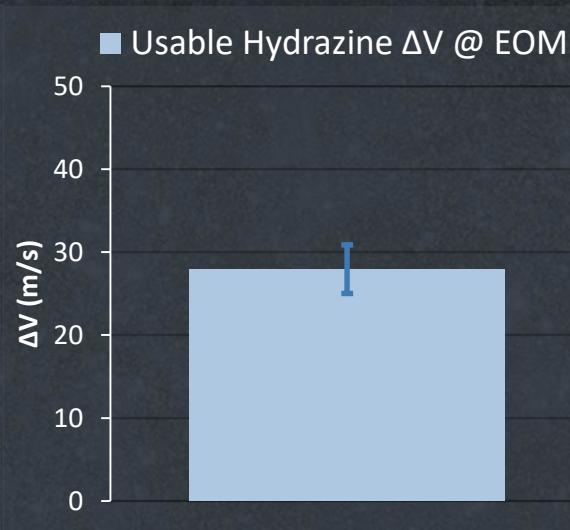
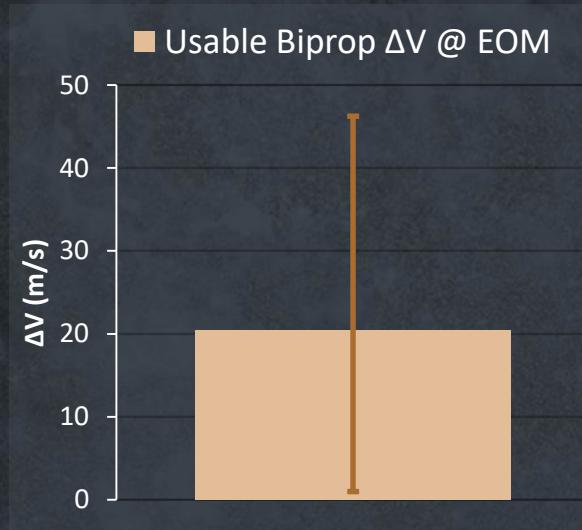
Proximal Pop-Down Scenario

Objective:

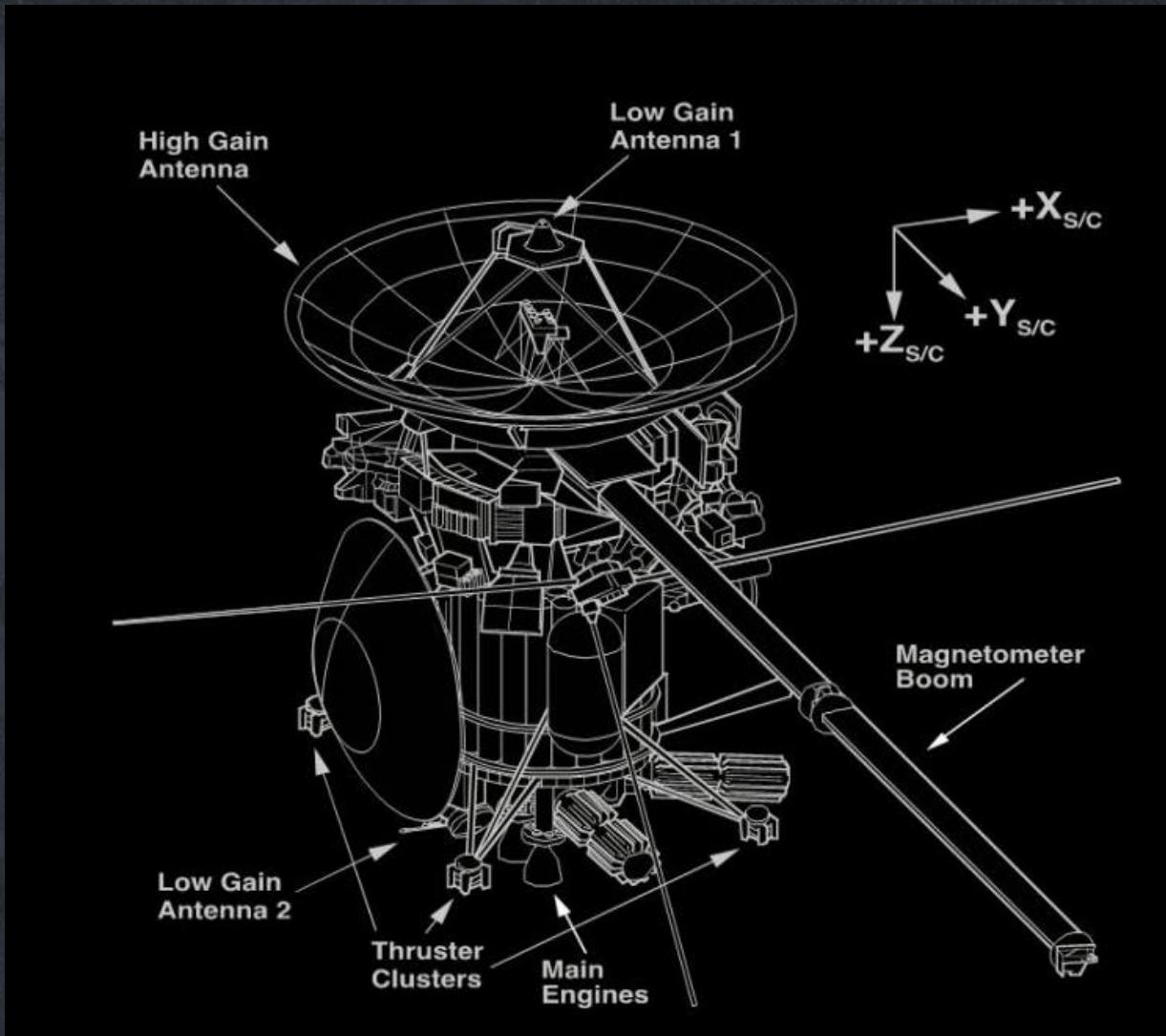
Determine the feasibility of lowering one of the final five periapses

Assumptions

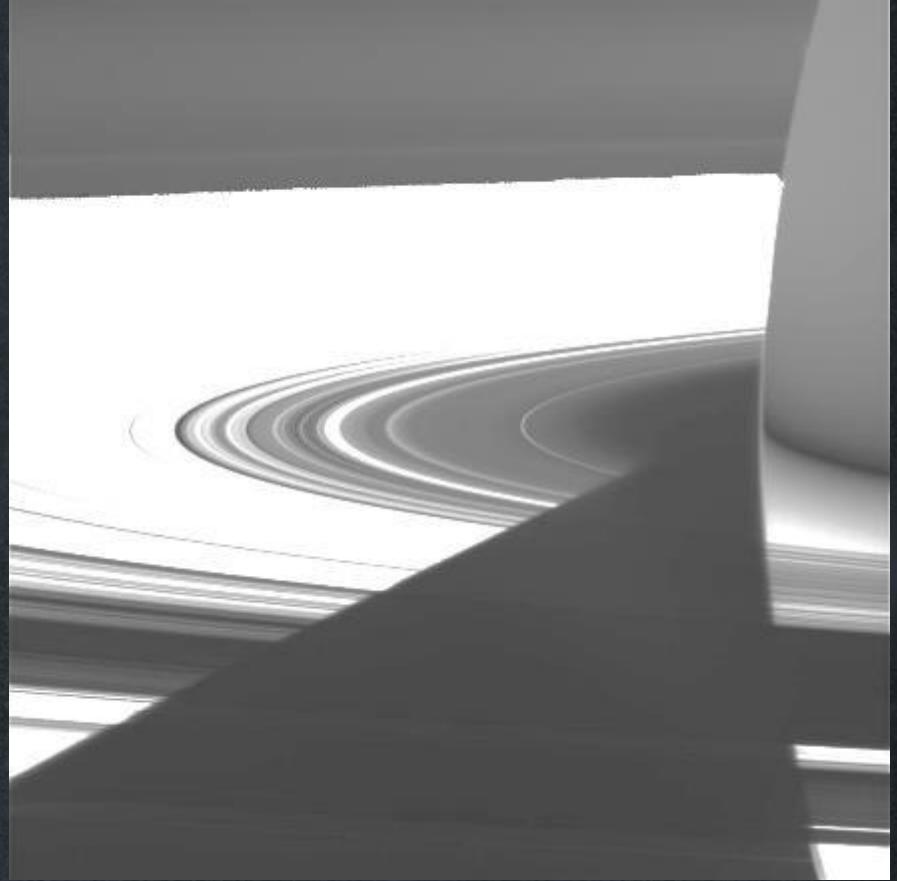
- The lower, the better (no lower limit other than s/c health & safety)
- Spacecraft operating nominally
- Sufficient propellant margins
 - Baseline MEA/bipropellant for pop-down maneuver
 - Potentially use RCS/hydrazine as back-up ($\max \Delta V \leq 4.0 \text{ m/s}$)



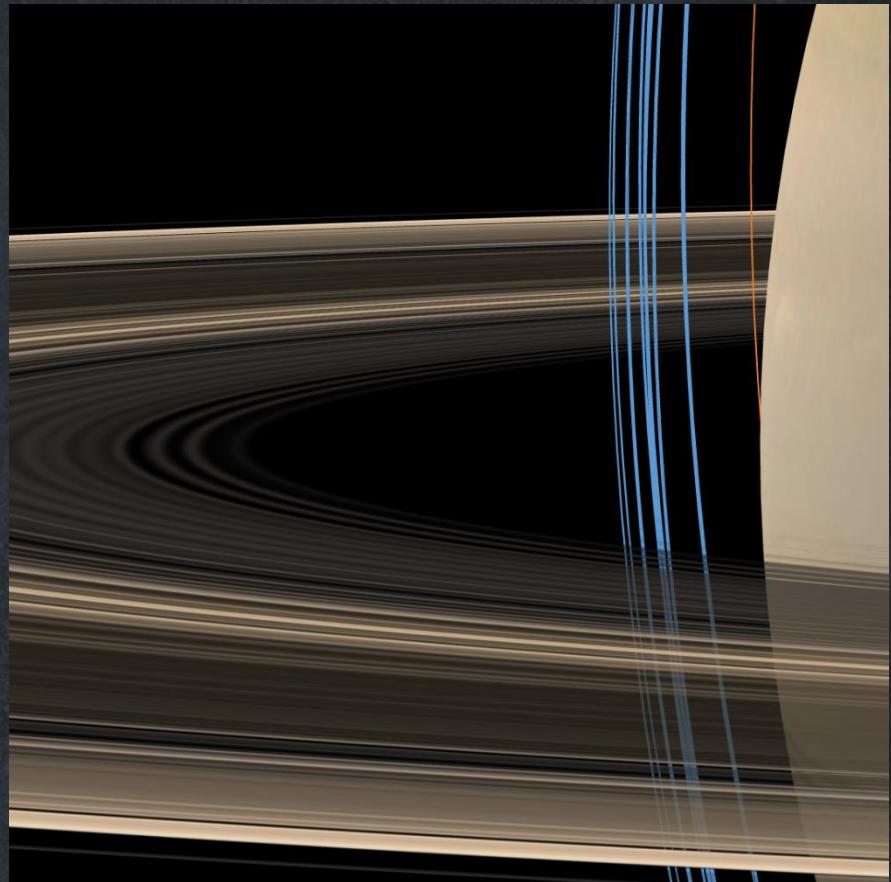
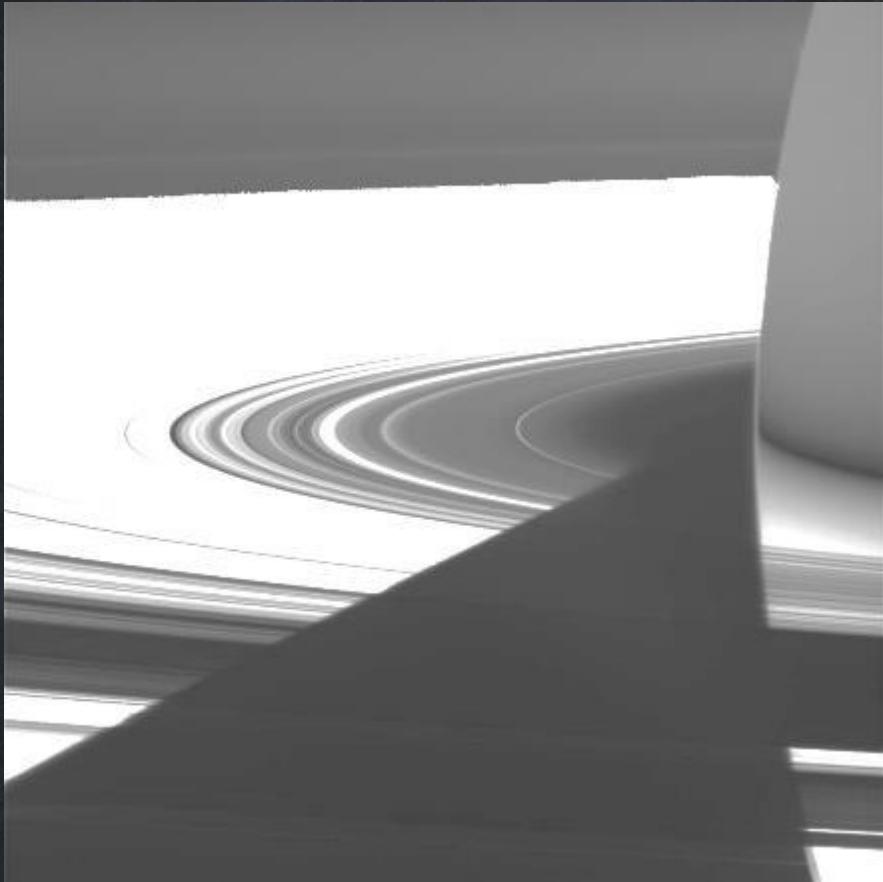
Cassini RCS Thruster Geometry



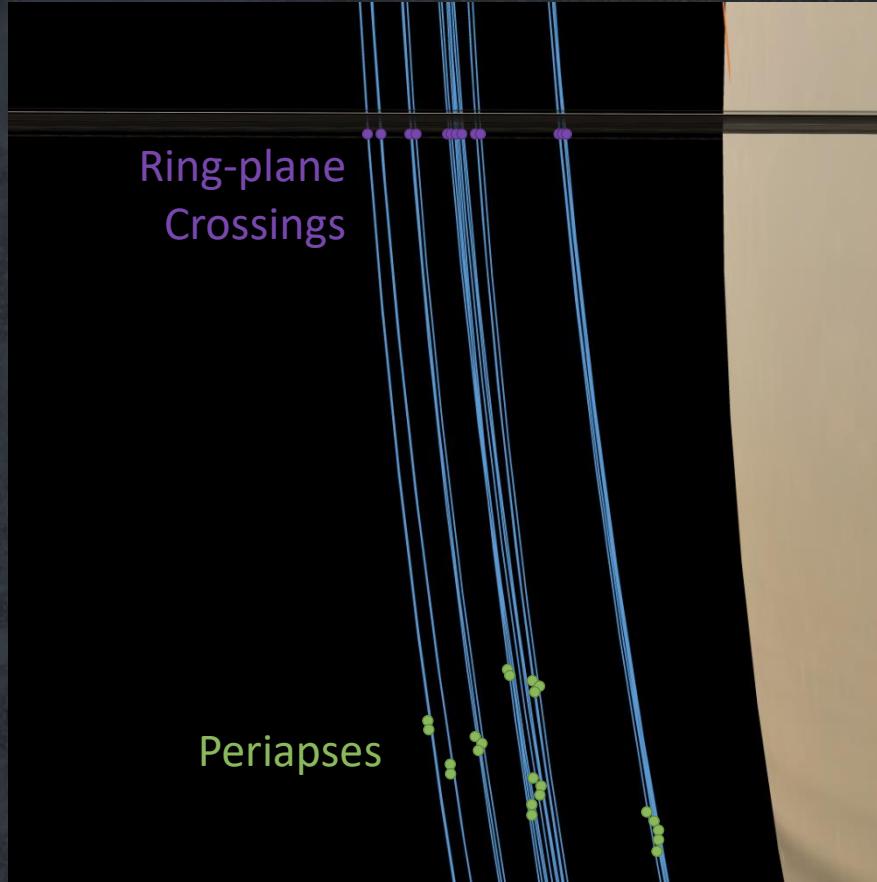
Proximal Environment



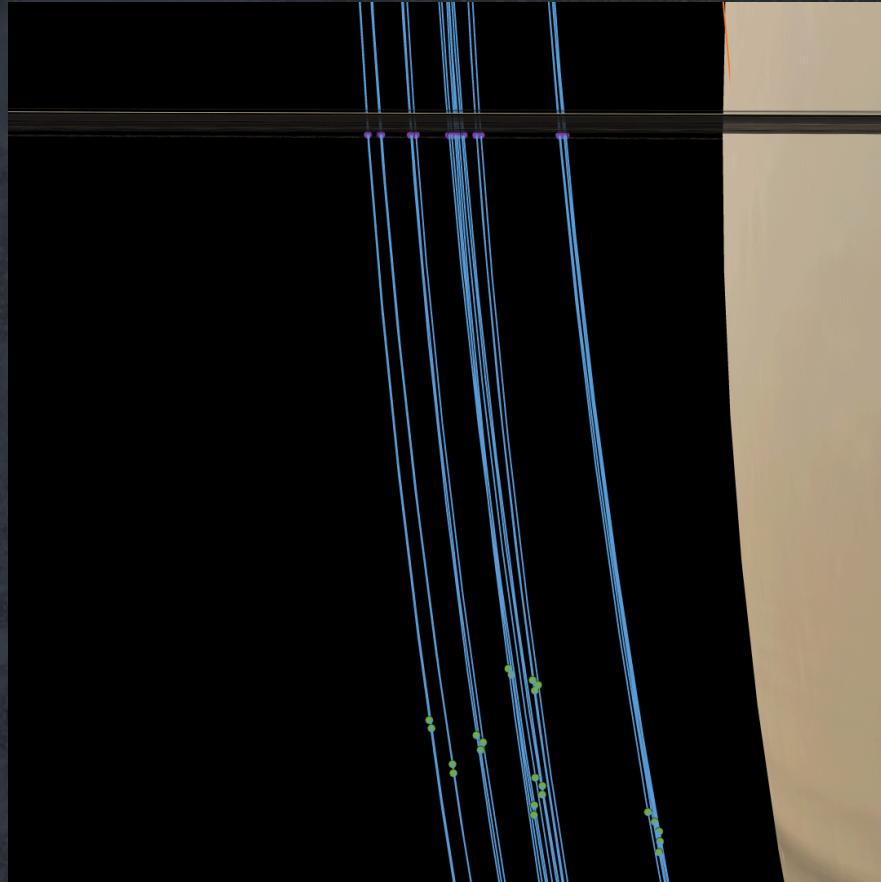
Proximal Environment



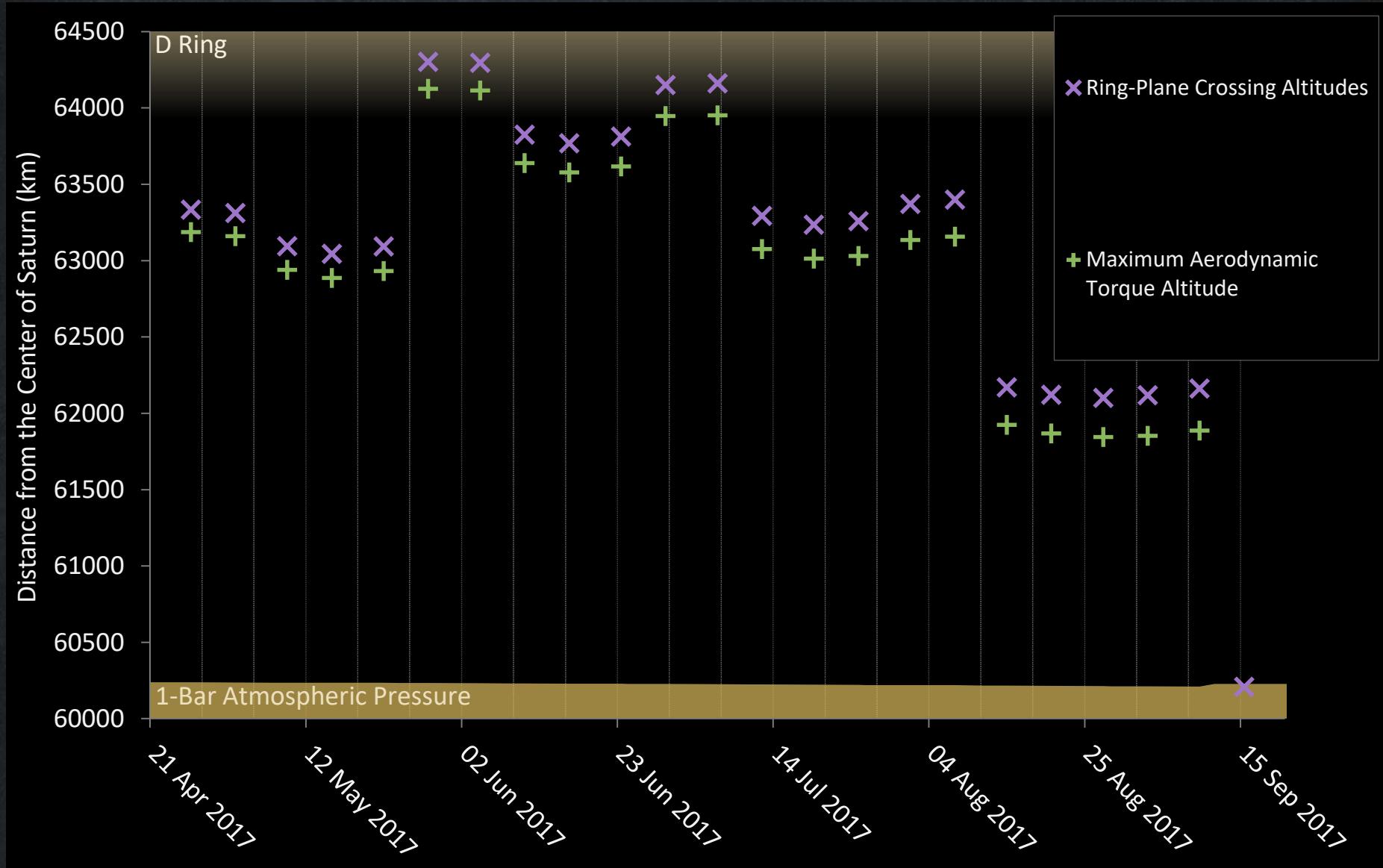
Proximal Environment



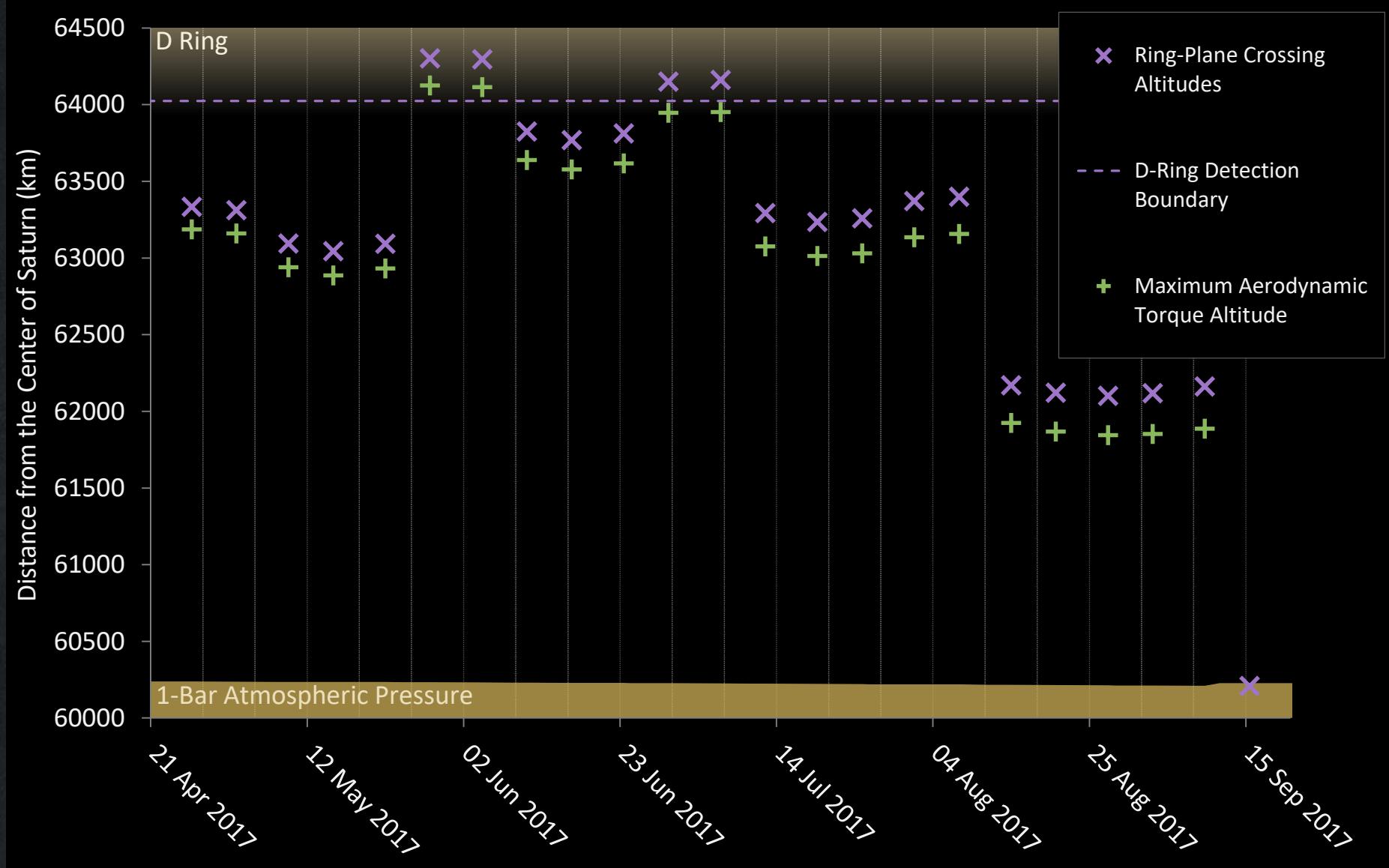
Proximal Environment



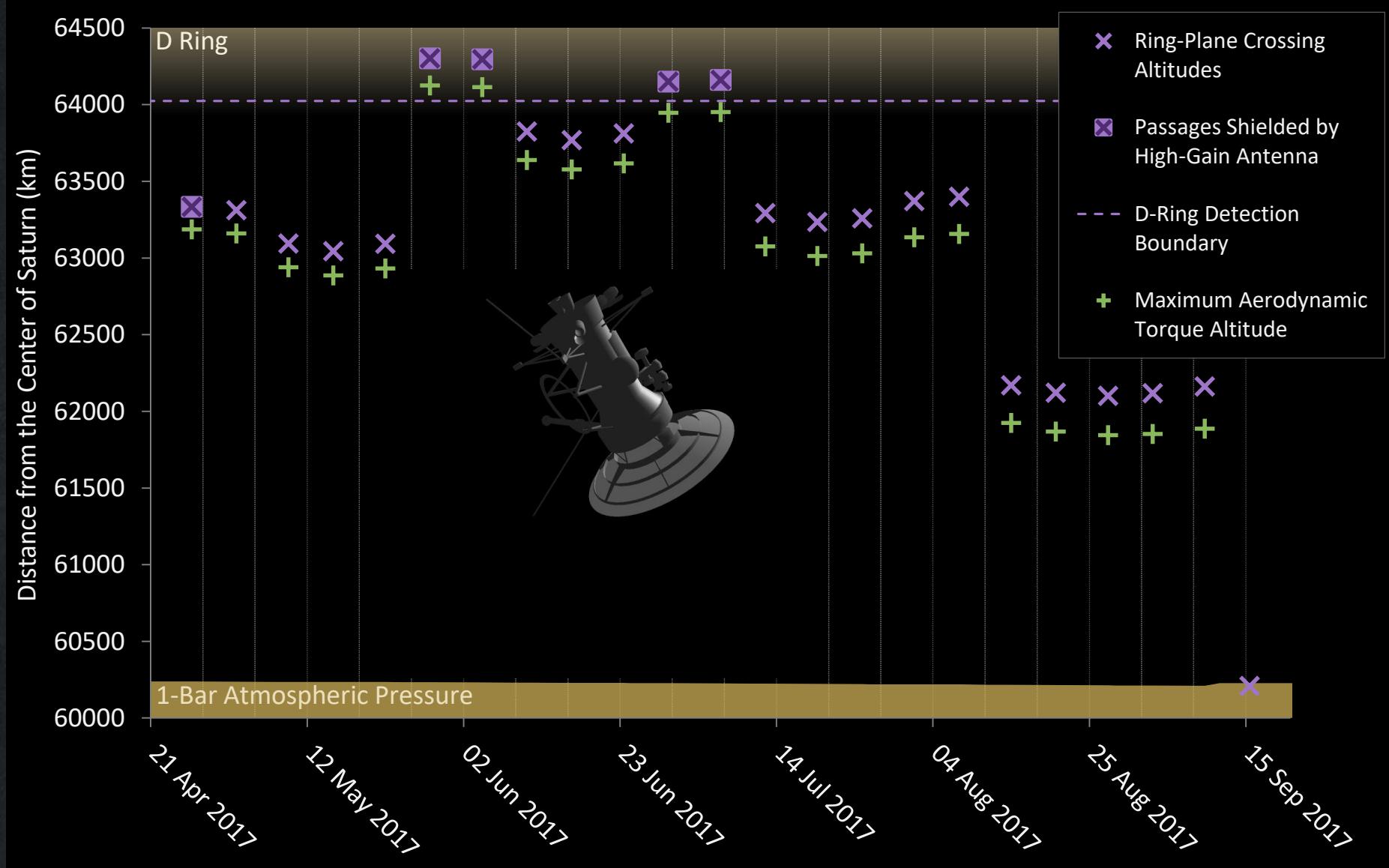
Proximal Environment



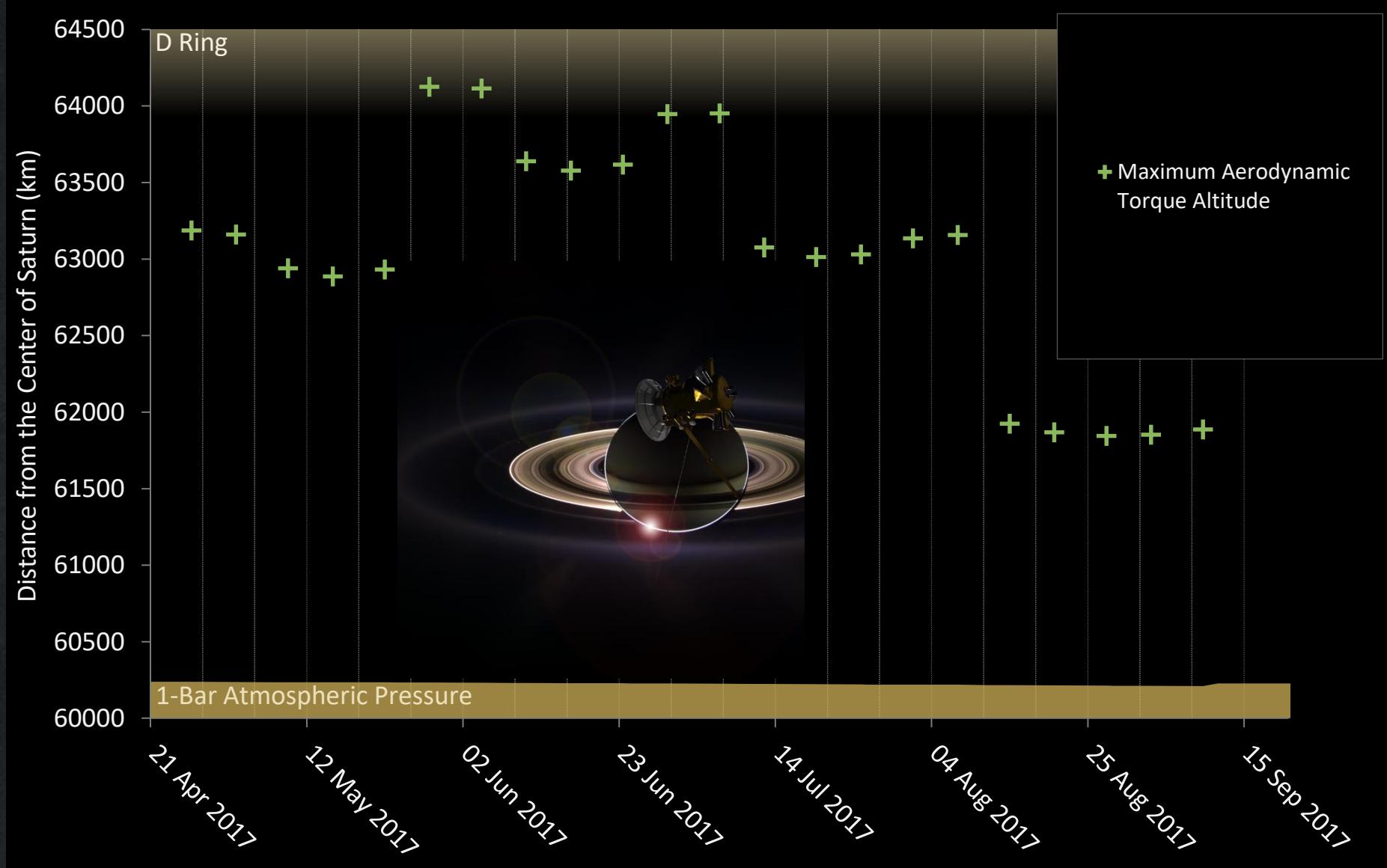
Proximal Environment



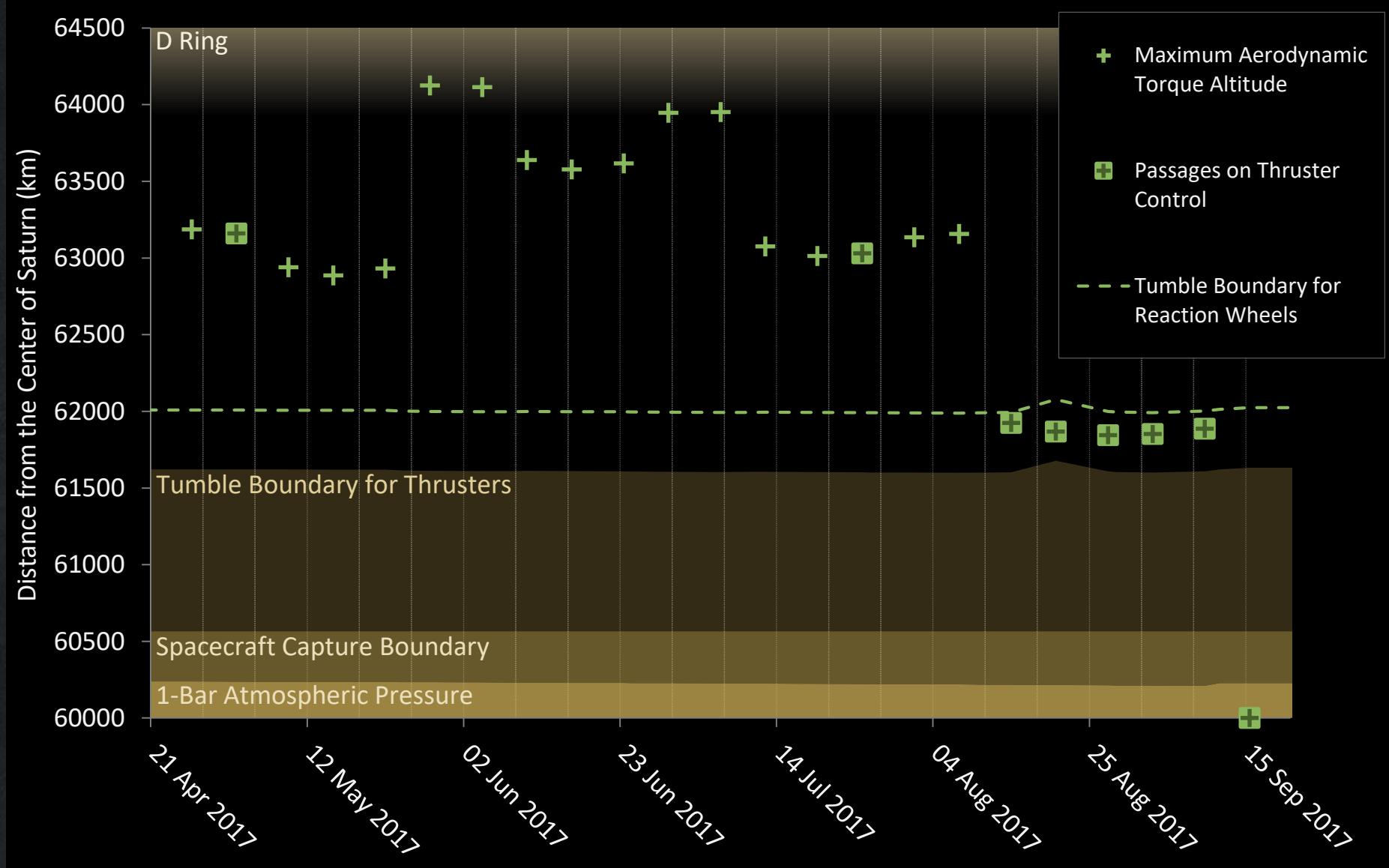
Proximal Environment



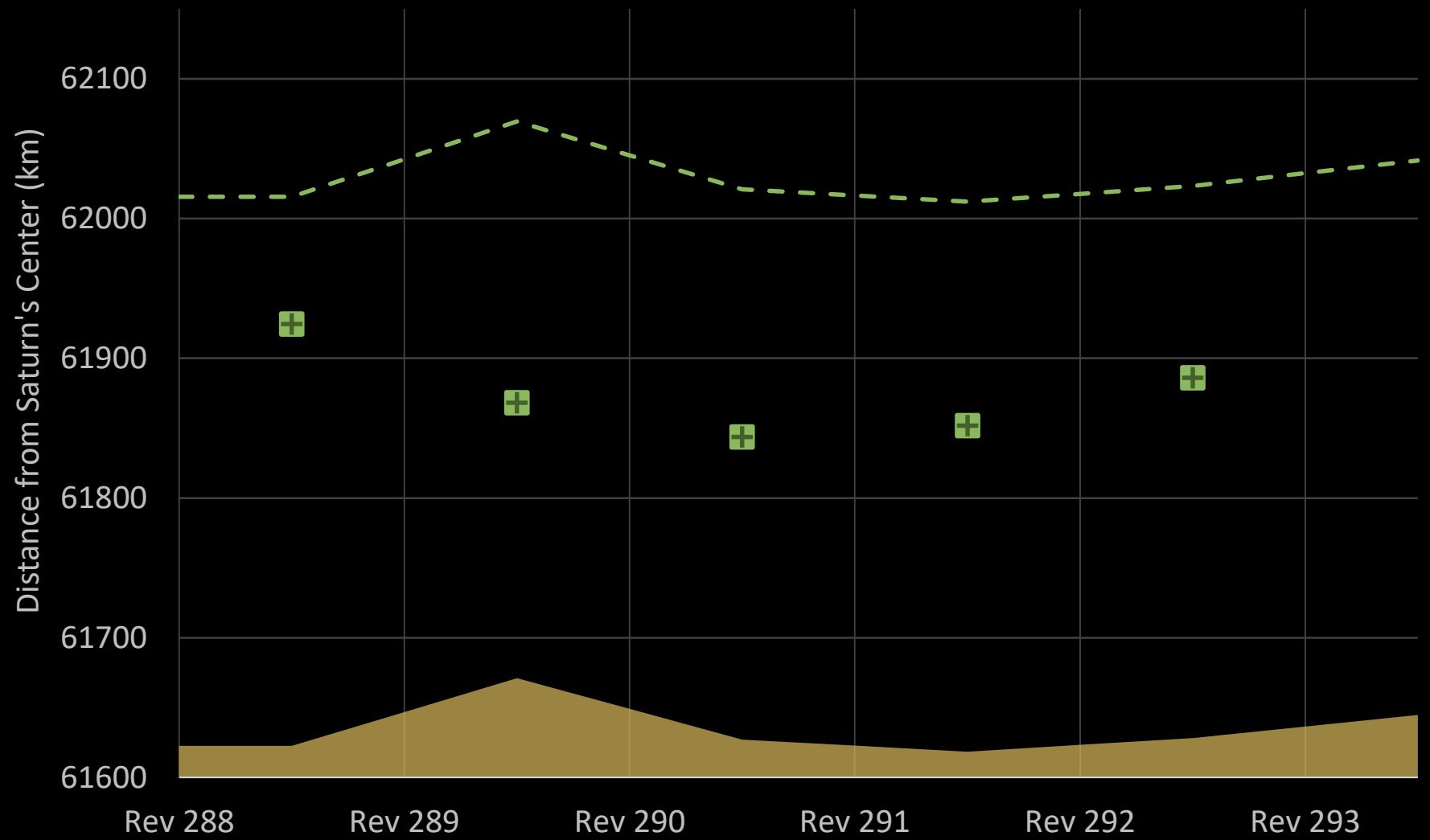
Proximal Environment



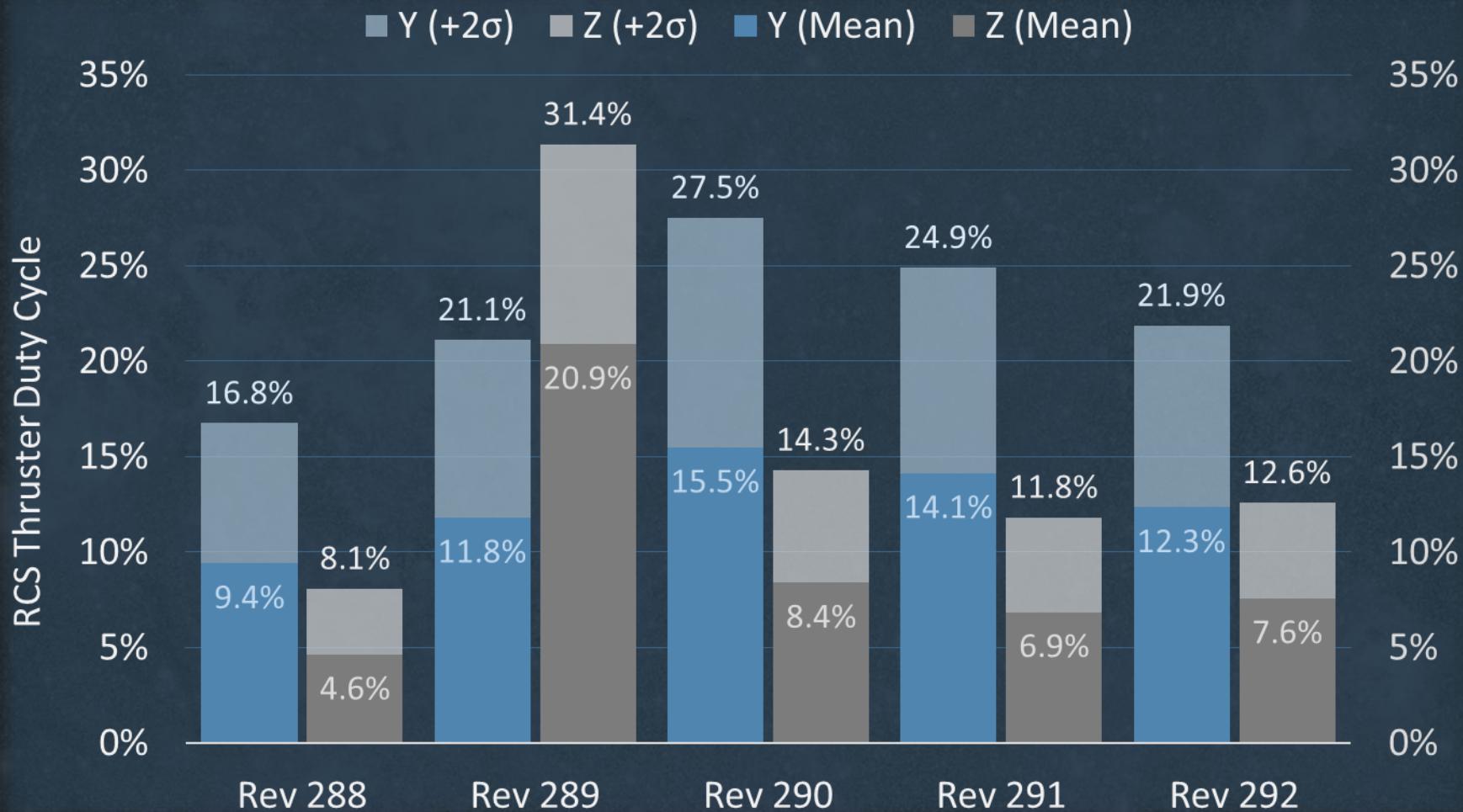
Proximal Environment



RCS Tumble (2σ) RWA Tumble (2σ) 150901 Ref. Traj.

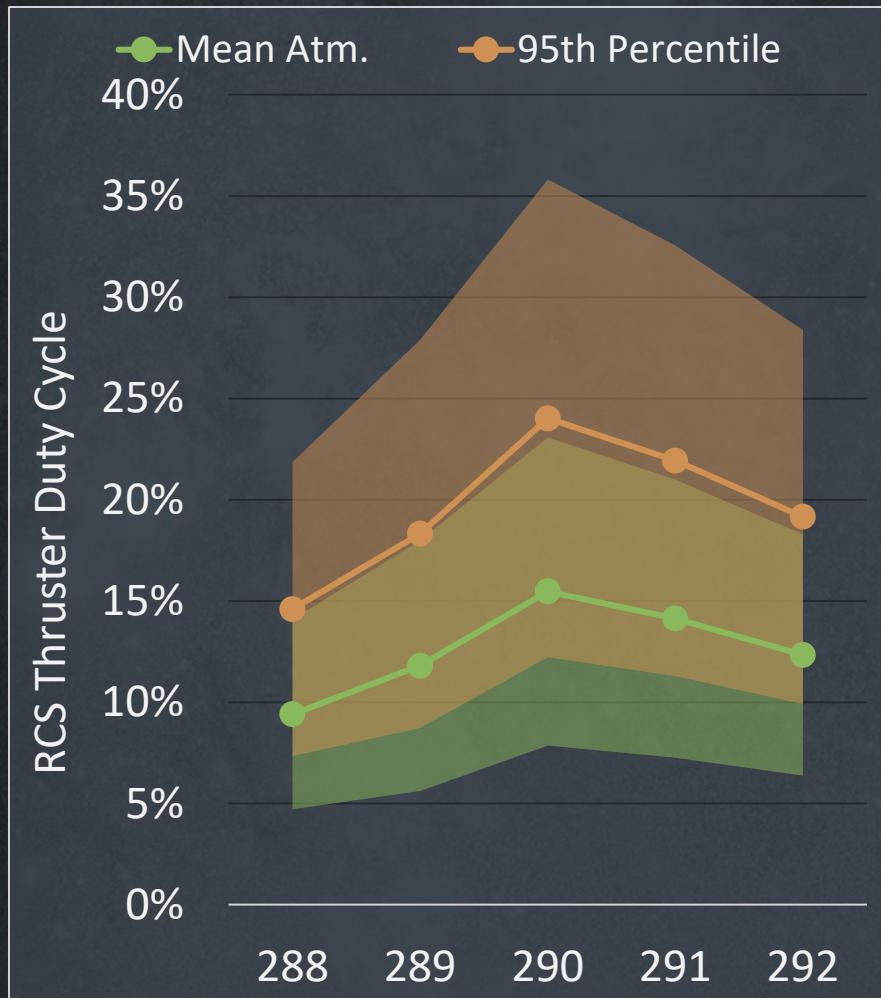


Mission Planning Status Report

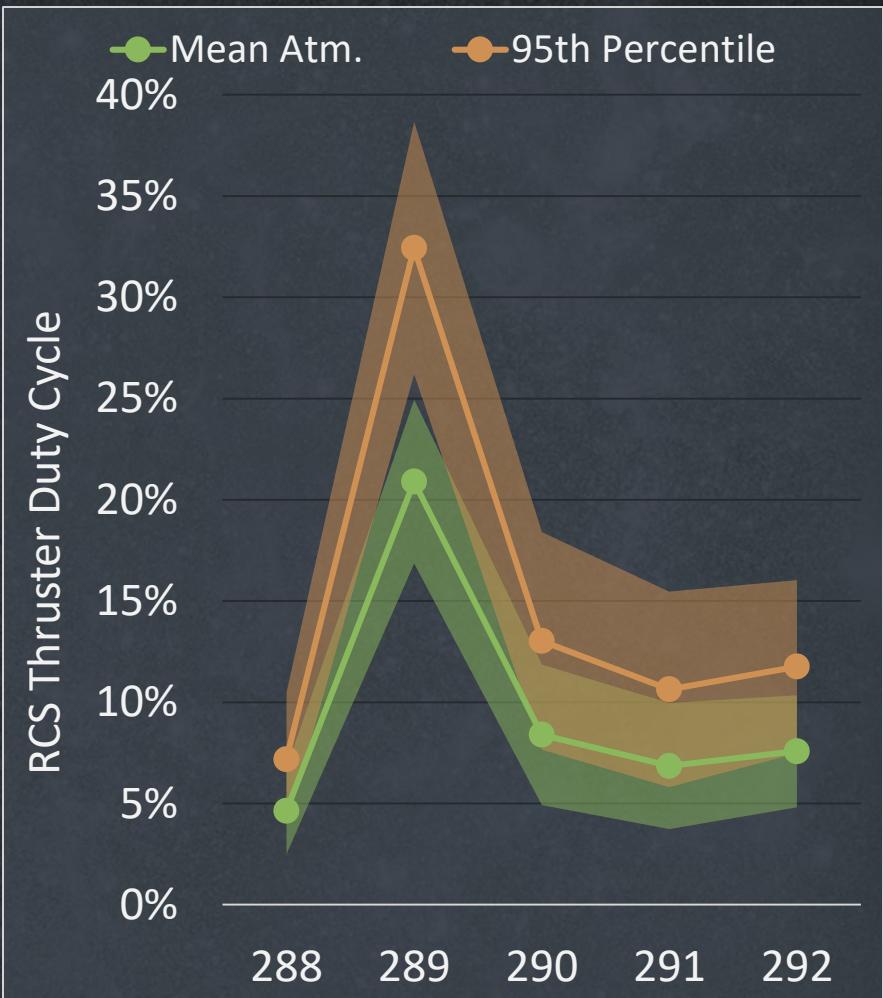


Atmospheric State Detection

Y-Thrusters

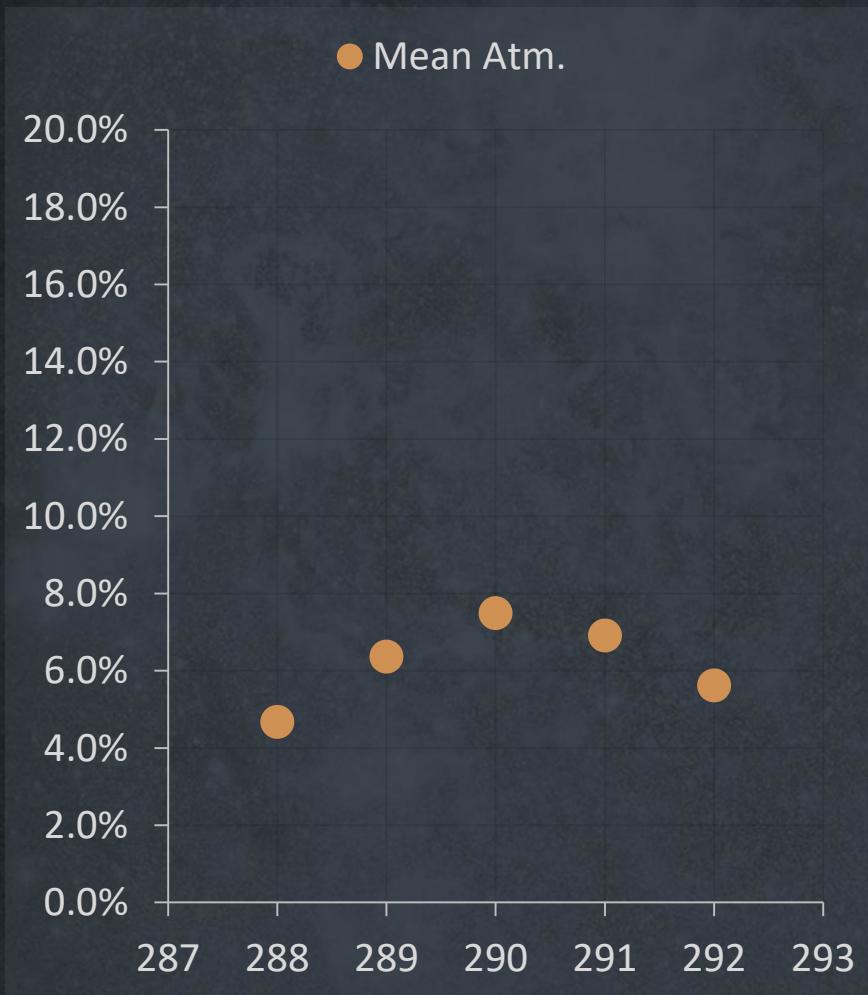


Z-Thrusters

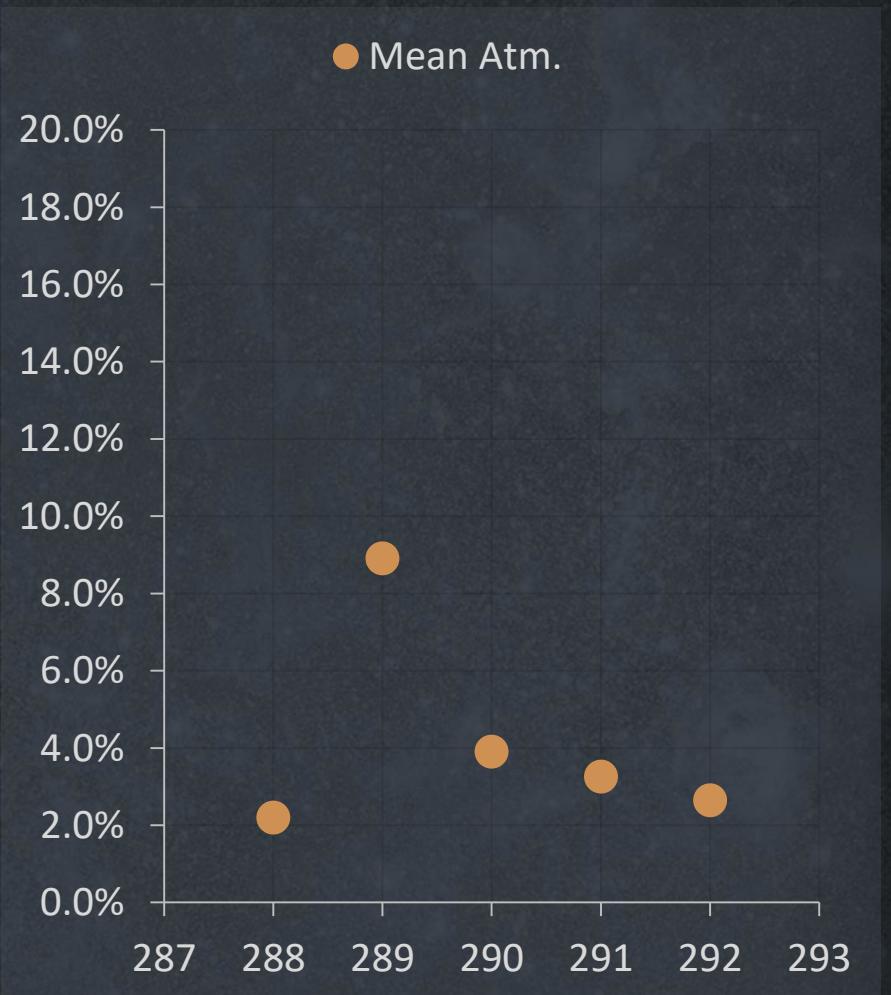


4.1 Detecting the Atmosphere

Y-Thruster Duty Cycles



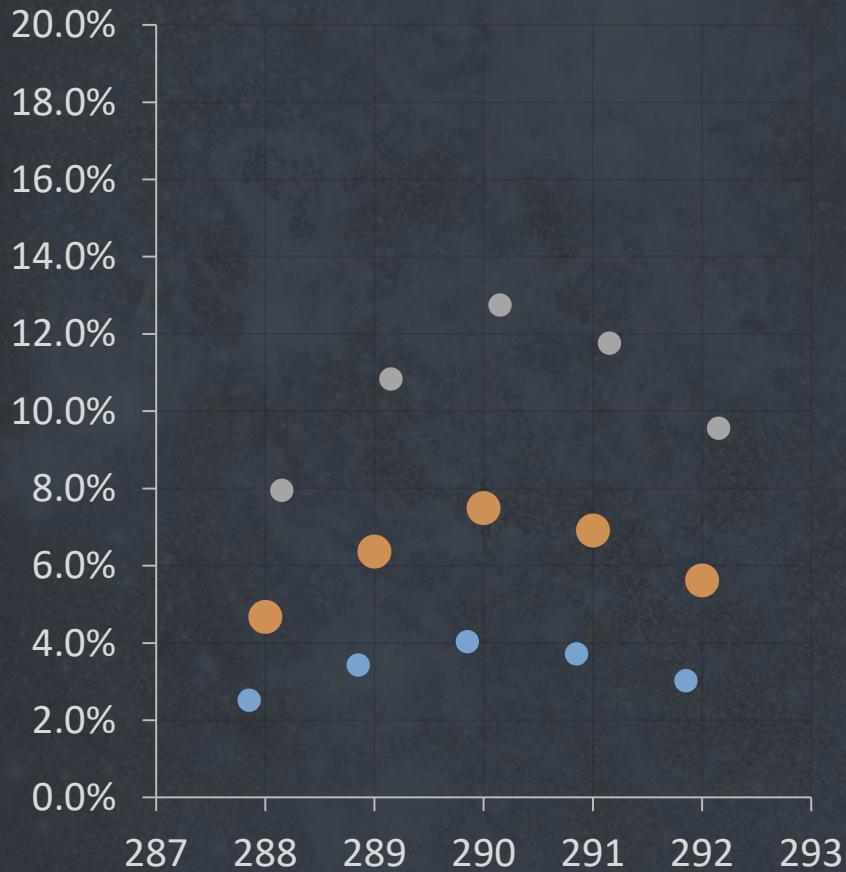
Z-Thruster Duty Cycles



4.1 Detecting the Atmosphere

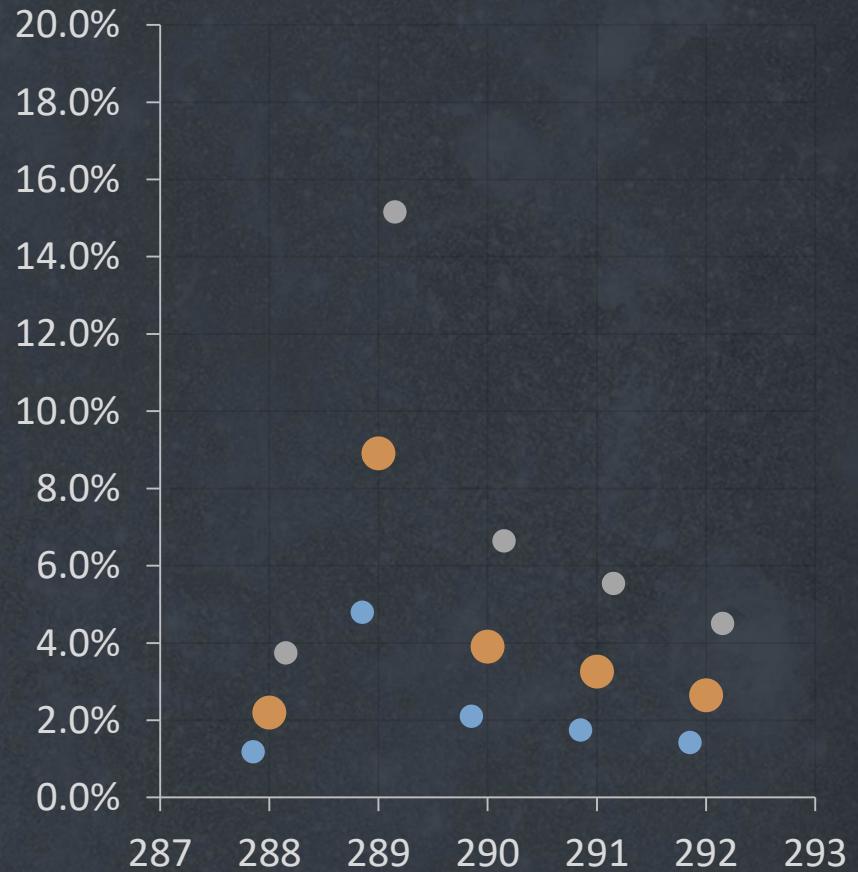
Y-Thruster Duty Cycles

● Mean Atm. ● 2 σ Low Atm. ● 2 σ High Atm



Z-Thruster Duty Cycles

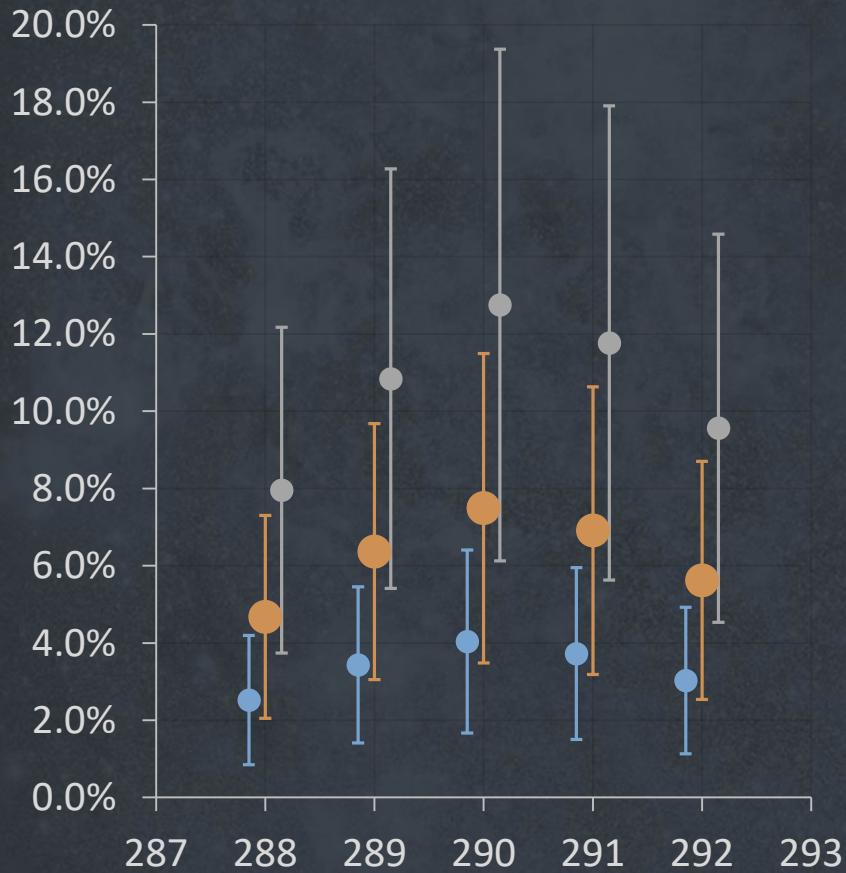
● Mean Atm. ● 2 σ Low Atm. ● 2 σ High Atm.



4.1 Detecting the Atmosphere

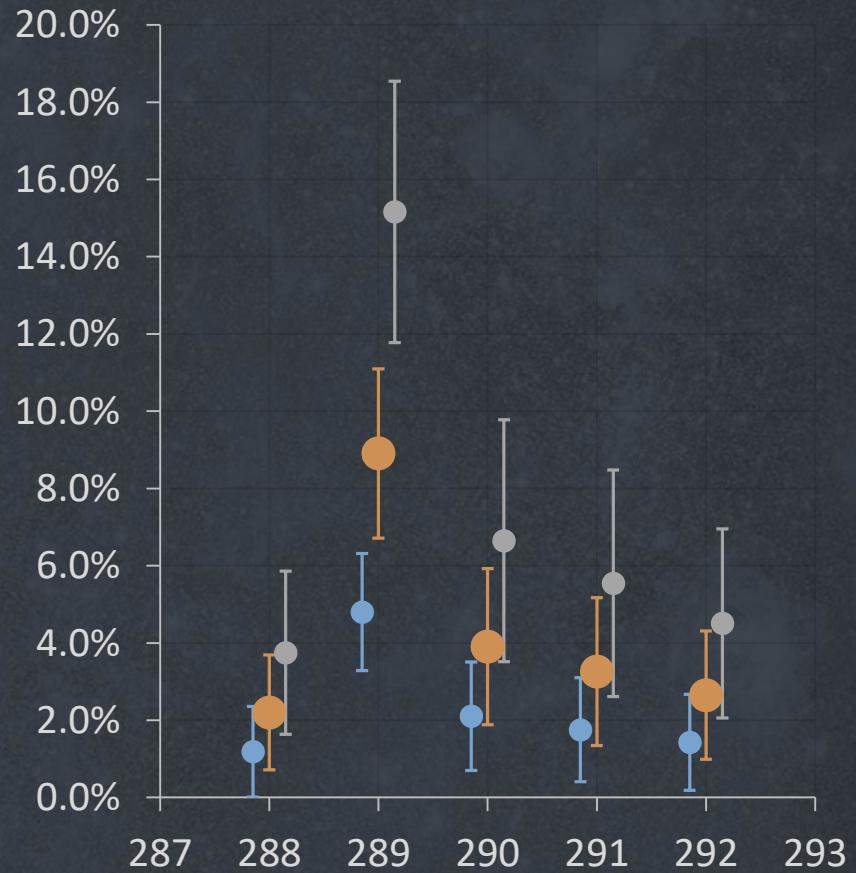
Y-Thruster Duty Cycles

● Mean Atm. ● 2 σ Low Atm. ● 2 σ High Atm



Z-Thruster Duty Cycles

● Mean Atm. ● 2 σ Low Atm. ● 2 σ High Atm.



4.1 Thruster Duty-Cycle Uncertainties



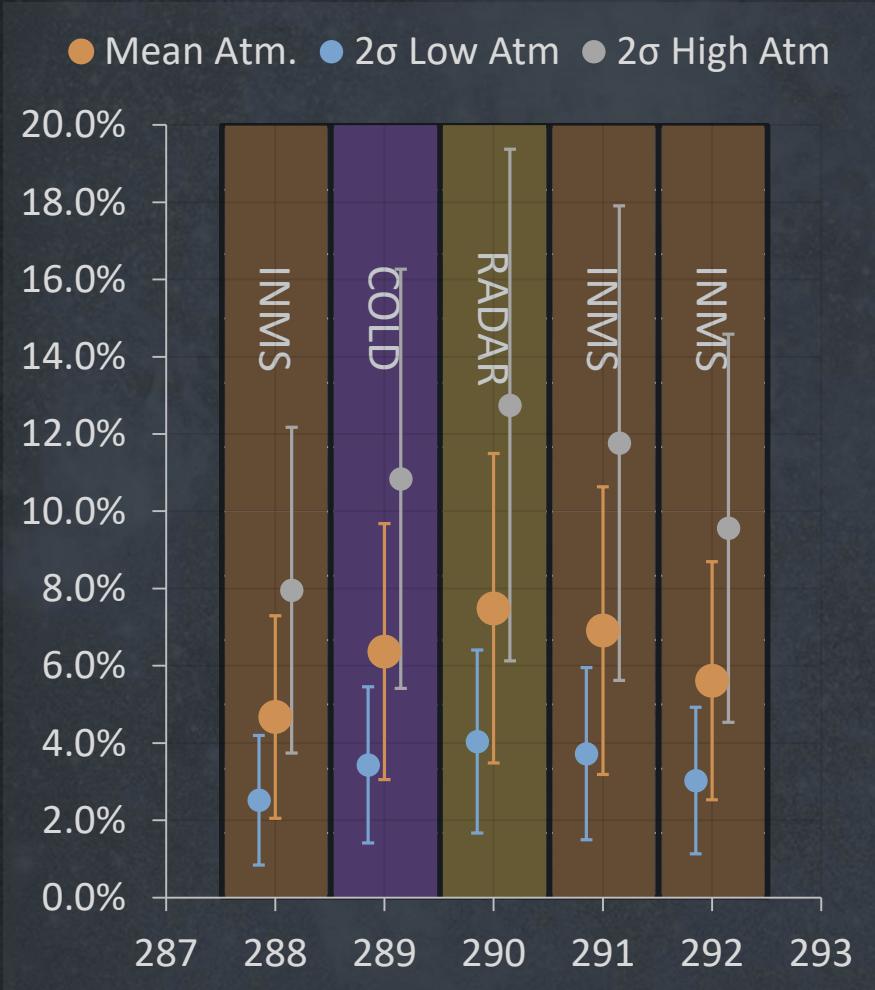
Source	Unc. (1σ)	Units
Duty Cycle Calculation	0.5%	---
Navigation		
Radius	6.9	km
Velocity	10	m/s
Spacecraft		
Drag Coefficient	0.033	---
Drag Area	0.117	m^2
Center of Press.		
CPx	0.011	m
CPy	0.204	m
CPz	0.080	m
Center of Mass		
CMx	0.003	m
CMy	0.007	m
CMz	0.019	m
RCS Thrust	0.010	N

4.1 Pop-Down Maneuver Location

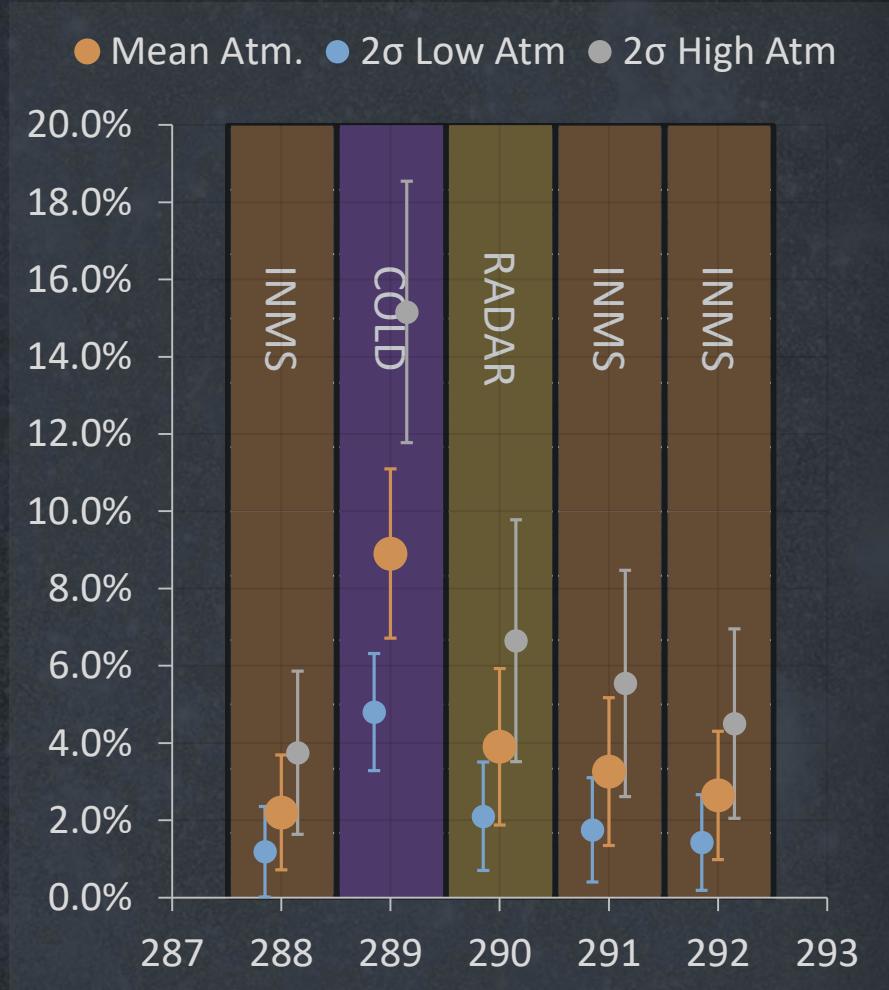


No earlier than Rev 290. Scenario baseline Rev 291, back-up Rev 292

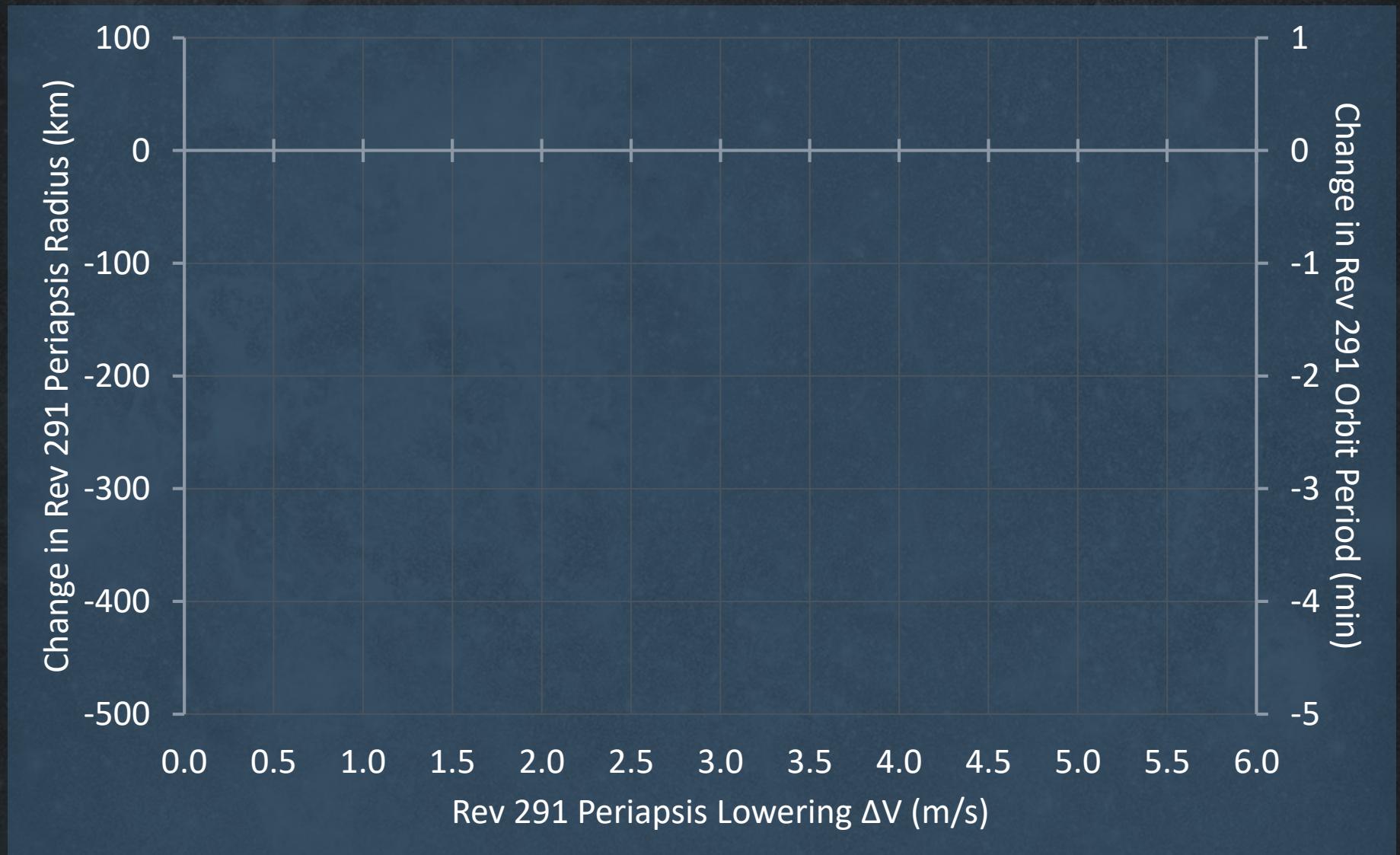
Y-Thruster Duty Cycles



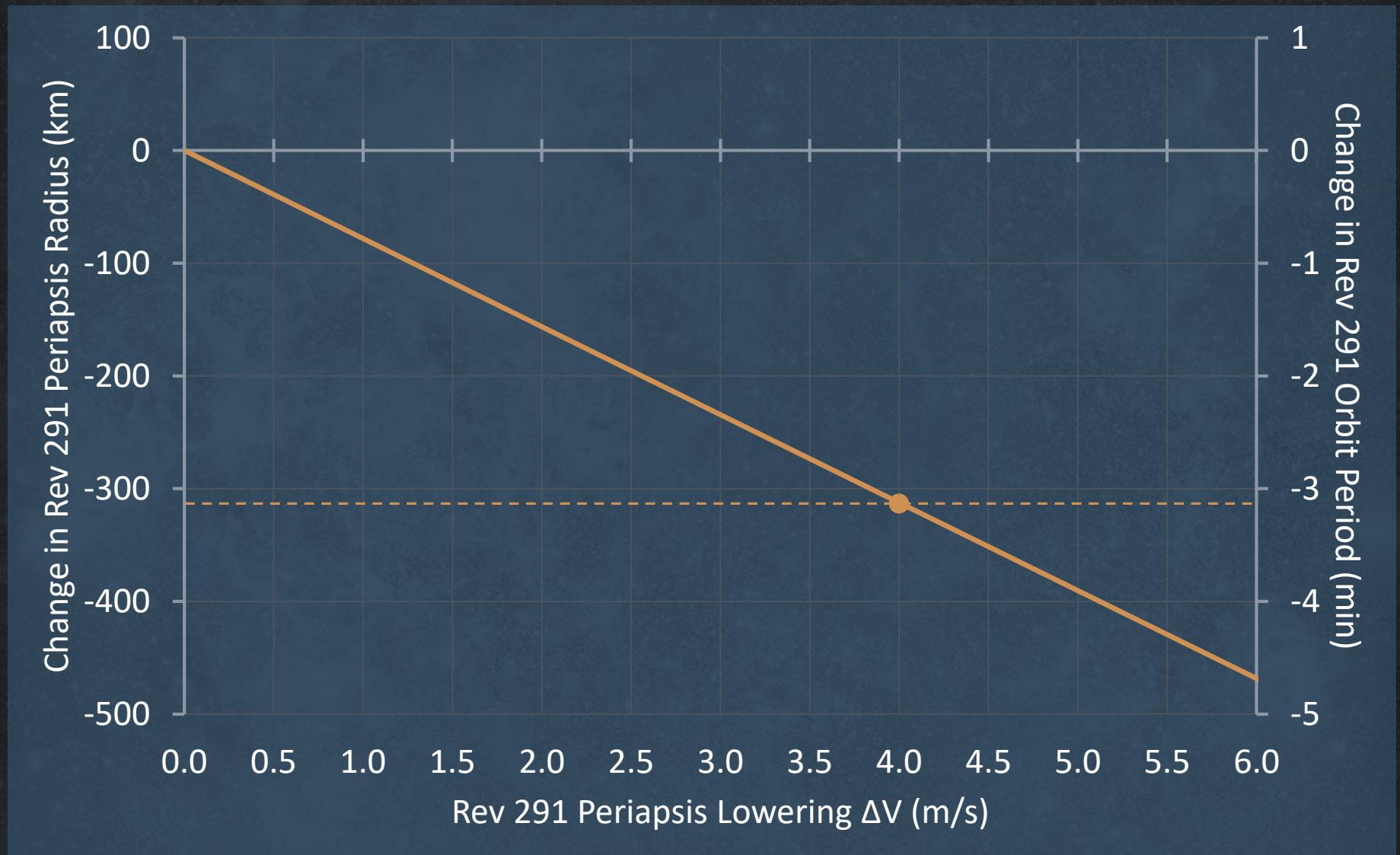
Z-Thruster Duty Cycles



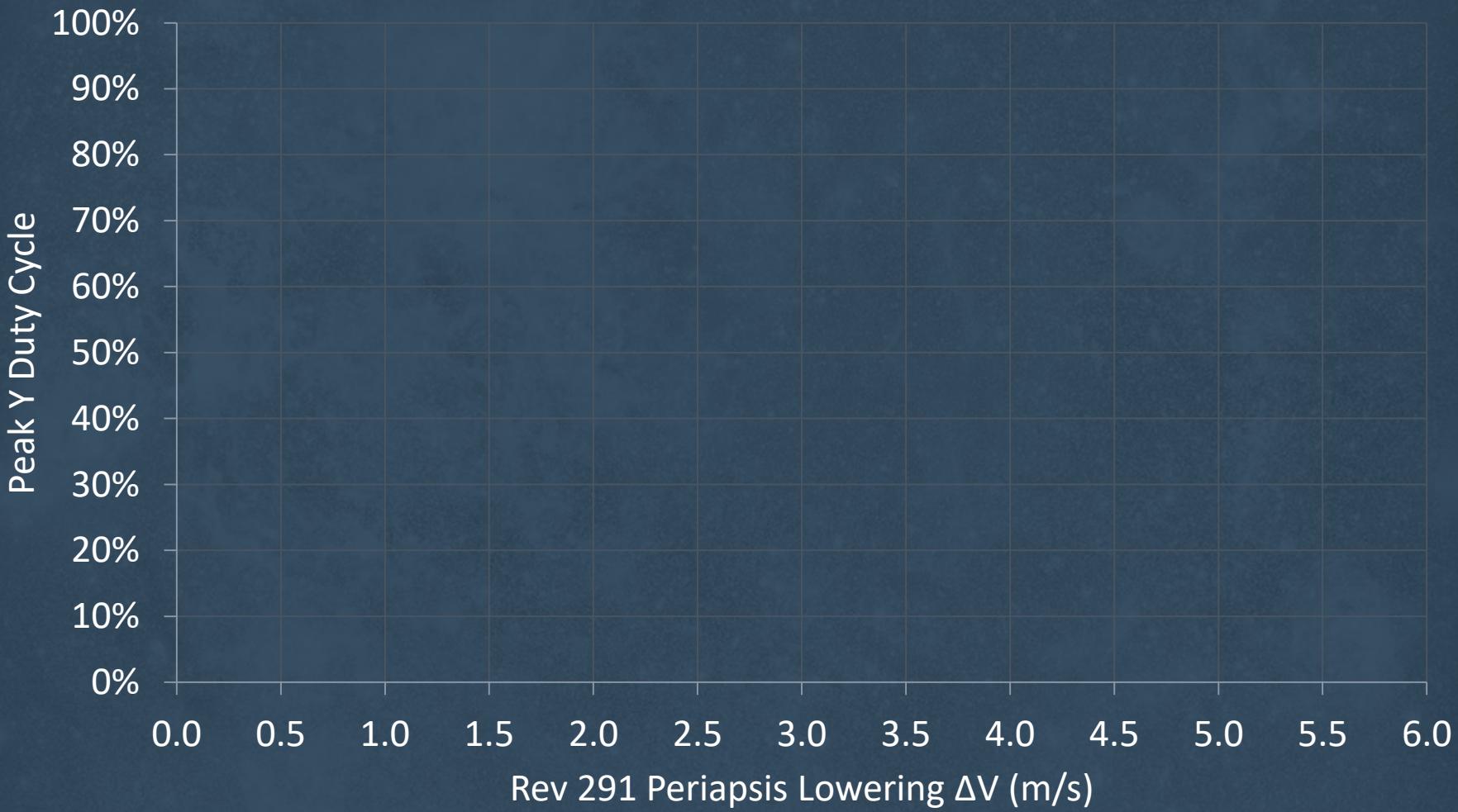
4.2 Pop-Down Maneuver Design



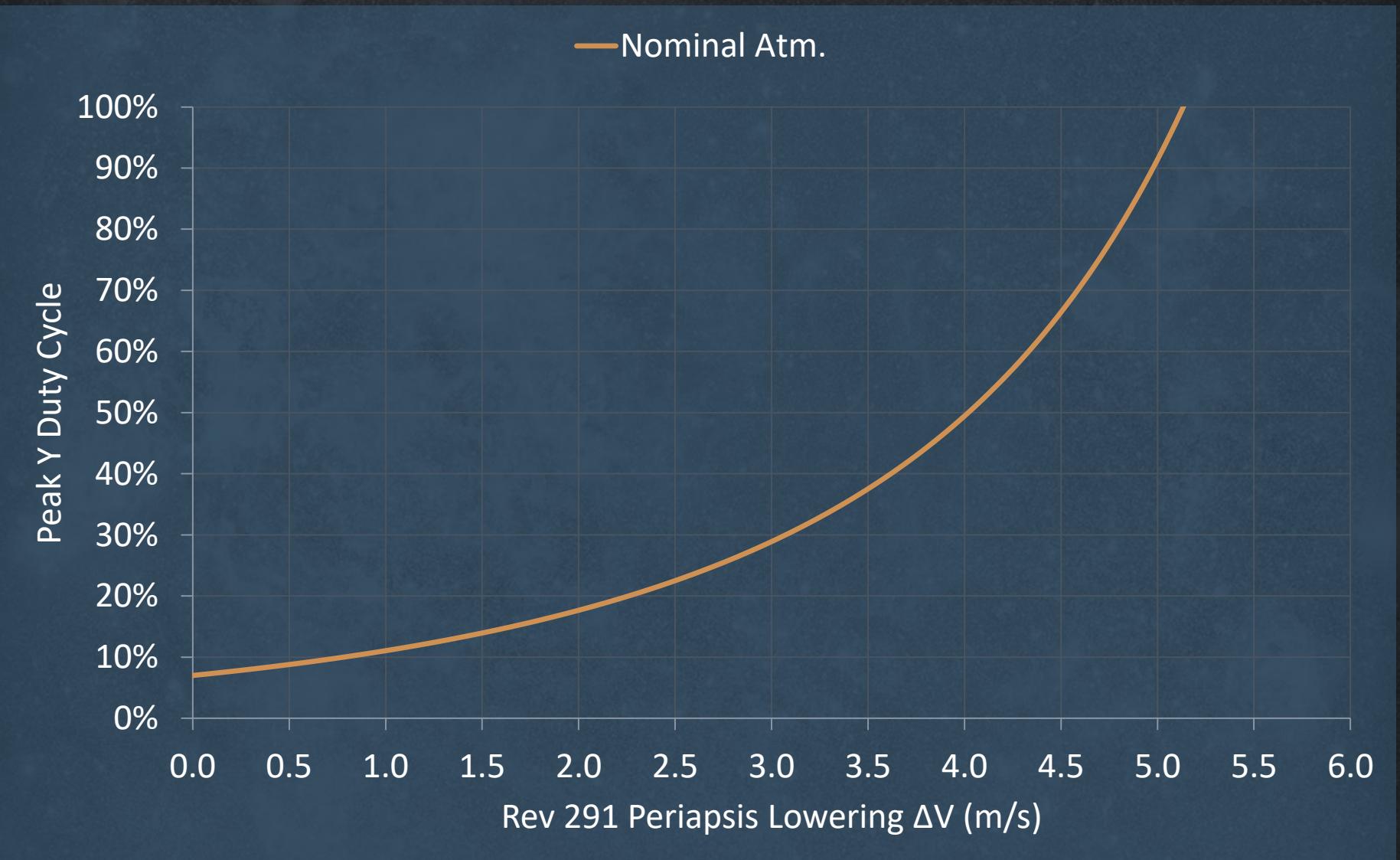
4.2 Pop-Down Maneuver Design



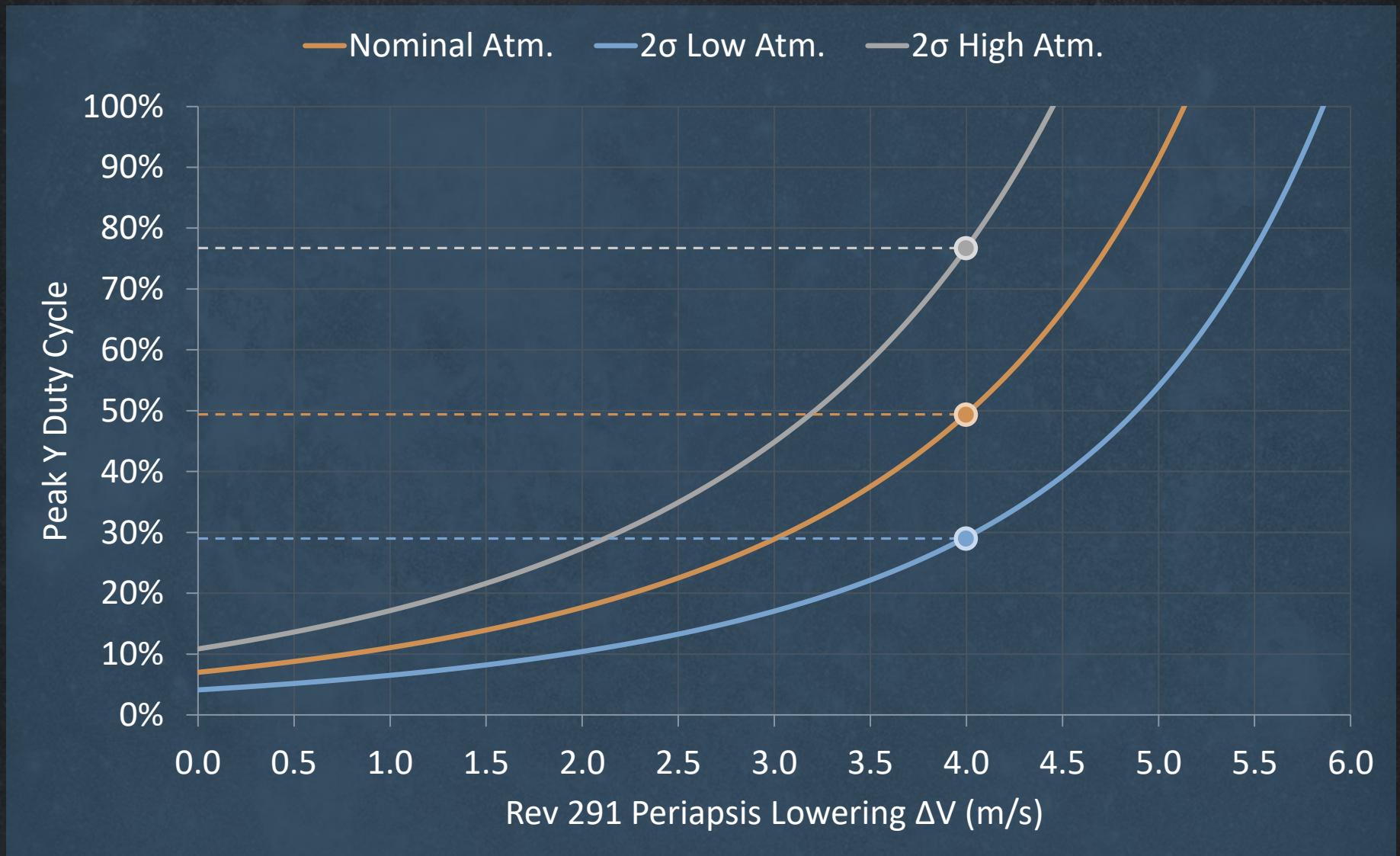
4.2 Pop-Down Maneuver Design



4.2 Pop-Down Maneuver Design

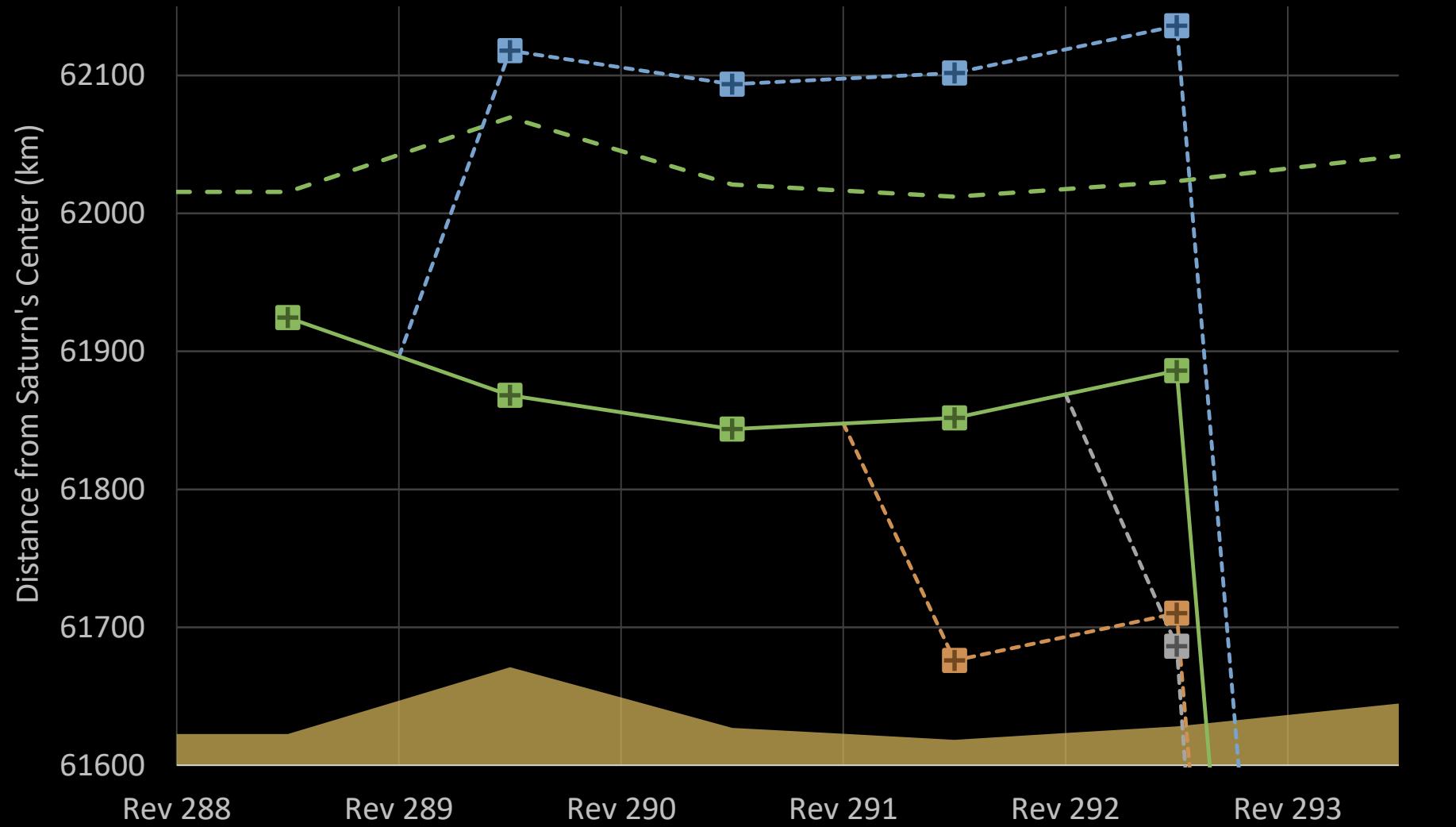


4.2 Pop-Down Maneuver Design

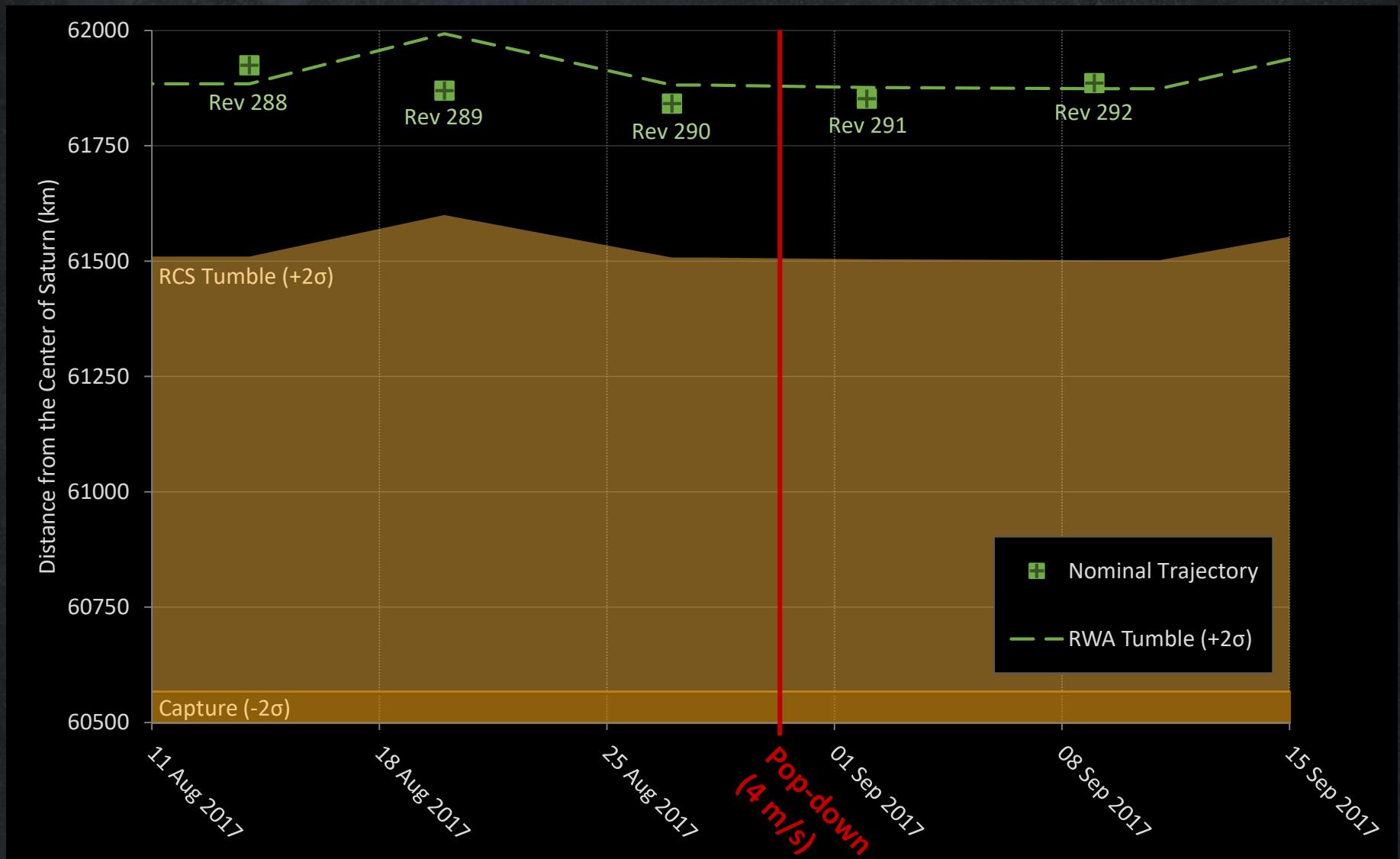


The Final Five

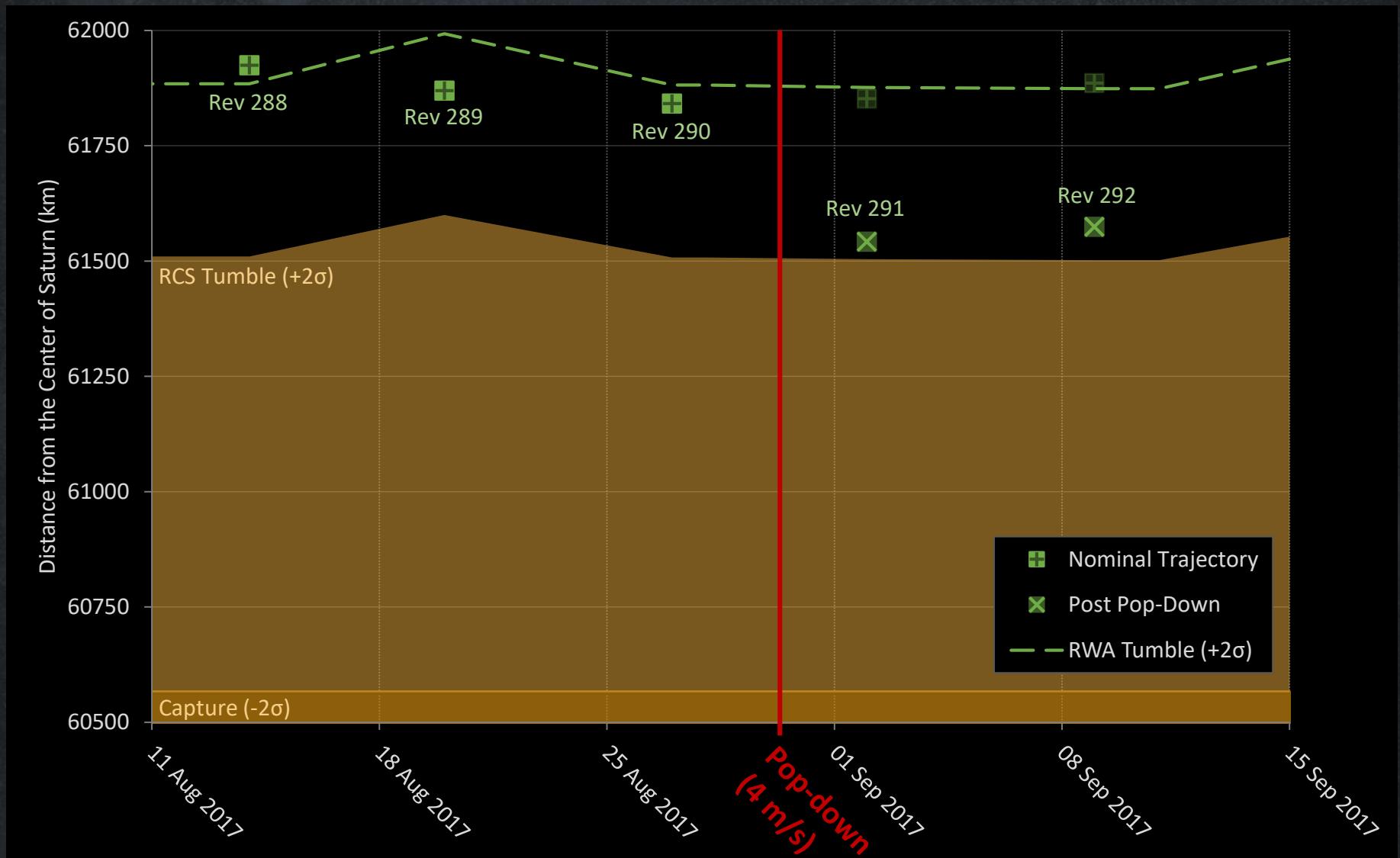
■ RCS Tumble (2σ)	— RWA Tumble (2σ)	+■ 150901 Ref. Traj.
-+■ Rev 289 Pop-up	-+■ Rev 291 Pop-down	-+■ Rev 292 Pop-down



4.3 Downstream Effects



4.3 Downstream Effects



4.3 Downstream Effects



Rev		Nominal Timing	Rev 291 Pop-Down Maneuver Magnitude				
			0.5 m/s	1.0 m/s	2.0 m/s	3.0 m/s	4.0 m/s
291	Apoapsis	30 Aug 2017 07:54	-00:00	-00:00	-00:00	-00:00	-00:00
	Periapsis	02 Sep 2017 13:23	-00:12	-00:24	-00:49	-01:13	-01:37
292	Apoapsis	05 Sep 2017 18:54	-00:24	-00:49	-01:37	-02:26	-03:15
	Periapsis	09 Sep 2017 00:24	-00:37	-01:13	-02:26	-03:39	-04:52
293	Apoapsis	12 Sep 2017 05:44	-00:49	-01:37	-03:15	-04:52	-06:29
	Tumble	15 Sep 2017 10:45	-01:01	-02:02	-04:03	-06:05	-08:07

Times are in mm:ss

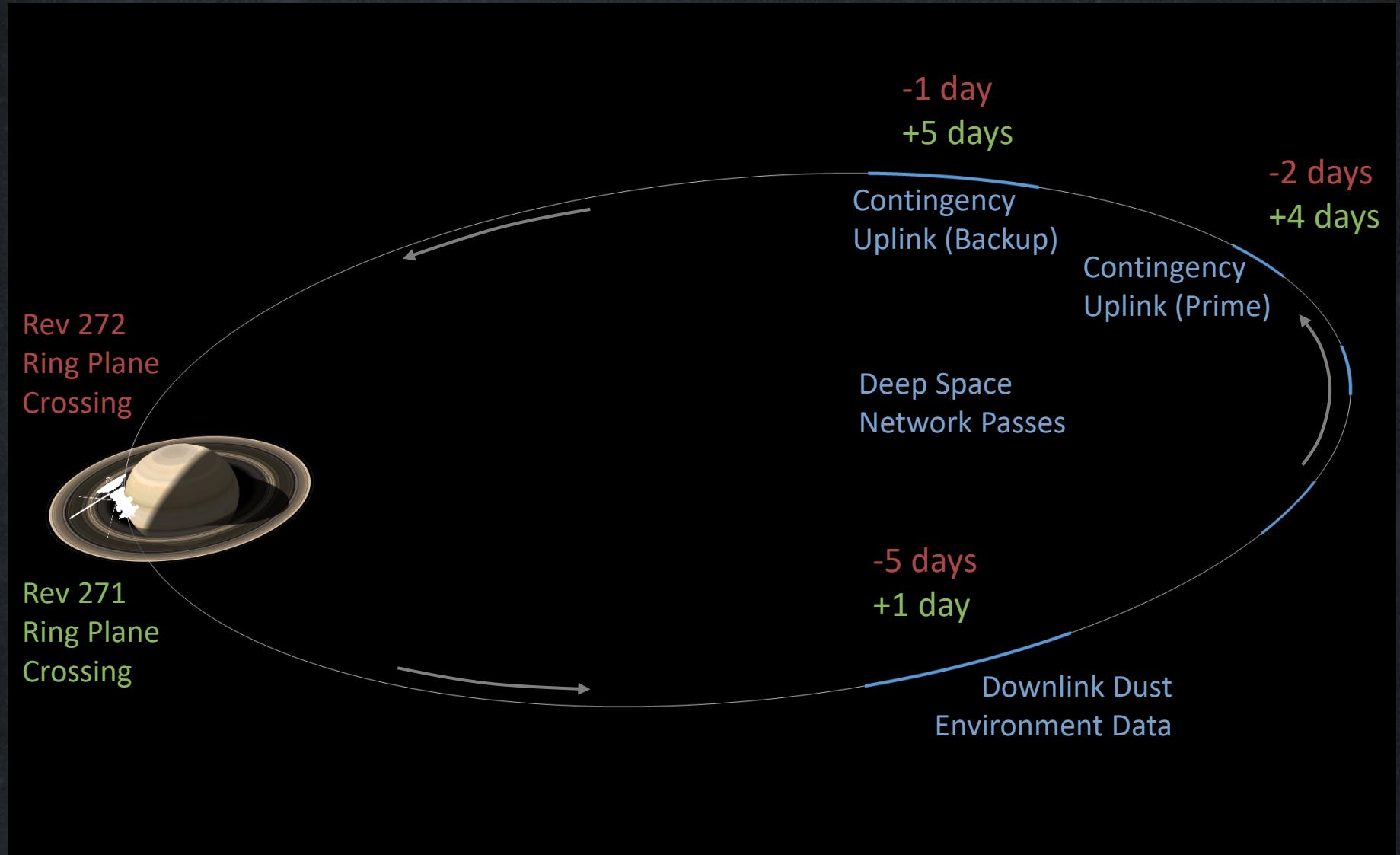
Negative times mean earlier than ref. traj.

4.4 Planned DSN Passes



Pass Type		Revs 290-291	Revs 291-292
Post Transit		2 ✓	1-2 ✓
Pop-Down		1-2 ✓	2 ✓
Post Mnvr.		1-2 ✓	2-3 ✓
Has req'd passes:		✓	✓

Pop-Down Timeline



5 Risk and Mitigations



Risk: Going to deep, tumbling

Mitigations:

- Complete more transits before pop-down
- Design to a predicted peak duty cycle of
 - Mean <70% (TBD)
 - and/or $+2\sigma <90\%$ (TBD)
- Perform multiple (smaller) pop-downs

Risk: Depleting bipropellant

Mitigations:

- Do nothing
- Follow biprop depletion during OTM procedure (i.e. use RCS during back-up pass)

Summary

- Atmosphere detection
 - Z-thruster duty cycle better detector than Y-thruster duty cycle
 - Rev 289 transit provides best resolution of atm. state
- Pop-down maneuver design
 - Max magnitude of single burn is 4 m/s on RCS thrusters
 - At Rev 291 apoapsis, 4 m/s burn would:
 - Decrease periapsis by ~300 km
 - Decrease orbital period by ~3 min
 - Increase peak thruster duty-cycle to 50% (77% for 2 σ -high atm)
- Downstream effects
 - Lower all subsequent periapses by about the same amount
 - Shift all subsequent periapses earlier (including entry)
- Reference Timeline
 - No changes to DSN tracking are required to implement a pop-down
- Risks & Mitigations
 - Main risk is going to deep and tumbling/safing
 - Several options are available to mitigate the risk

Questions?

Cassini *GRAND FINALE*



-Yeah, we're pretty awesome